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The Petrography and Petrology of the Cambrian Manganese-bearing Sediments of West Merionethshire(North Wales).

Part 1 of Thesis presented by

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in candidature for the degree of Philosophiae Doctor of the University of Wales.

April. 1937.

Manganese Rocks of Belgium.

Dr. F. Corin.

Letter from W. Campbell Smith, of the British Museum. 21st. June '38

Dear Professer Lewis,

Dr. Corin of the Belgian Geological Survey sent me a letter of which I enclose a copy. He asked me if I could show it at a meeting of the Geological Society, as a contribution to the discussion on Dr. Woodland's paper, but as that was not possible I am sending it to you.

I told him that the author would probably write to him direct.

Yours sincerely,

(W. Campbell Smith)

Keeper of Minerals.

COPY

Belgian Geological Survey,

Brussels.

30th May, 1938.

Dear Dr. Campbell Smith,

I came across a proof of th e minutes of the meeting of the Geological Society of L ondon, held on May 20th 1938, where Prof.H.P.Lewis presented a note on the manganese-ores of West-Merionethshire.

This interested me in that manganese-bearing ores or shales occur among Belgian rocks that are supposed to be Upper-Cambrian, and because these occurrences display also spessartite-garnet, chloritic material, sometimes yellow and supposedly manganiferous, sometimes rhodonite, and more often rhodochrosite.

The Belgian manganese-ores are still mined in the Lienne Valley, where they occuras a thin layer of poor, iron-bearing oxidized ore. Rhodochrosite is conspicuous in some veins, sometimes with sulph urated minerals, a green chlorite, and also carpholite. Blaise and myself have recently discussed the occurrences. Spessartite has recently been found there by Dedycker in a thin bed above the ore.

Other ores were mined in the past near Lierneux. X. Sainier describes them shortly as being silicated in depth,, an d dyke-like in shape, but the mines are no longer open. Oxidized ores occur as lumps of concretions of colloidal origin, in the shales near Ottre.

The region is not metamorphic in the Lienne Valley; it is more so towards the south-east, but it never reaches th e biotite zone, even in the well-known locality of Salm-Chateau, near Vielsalm. It is remarkable that the country-rocks are evidently more rich in spessartite and harmatite where some met metarmorphism is conspicuous, but some layers are always spess-artite-bearing.

At Salm- Chateau, rhodochrosite develops as porphyro-blasts, erroneously described as spessartite by Anten, and shown by Belliere tobe carbonate. Veins with dewalquite (or ardennite) and other minerals including a manganiferous yellow chlorite, occur there. Ihave shown that they develope bigger spessartite-crystals along their borders, but other veins, containing andalusite, point to some thermal influence. Spessartite develops also close to a malachite-bearing quartz vein.

The occurrences of spessartite is better known from a high-grade wetstone called "coticule" , of wh ich Salm-Chateau is the typical locality. Here spessartite in tiny euhedral crystals is mixed with chlorite and sericite, and th e adjoining rock contain s in addition, haematite-flakes that make it turn violet or blue instead of the pale yellow colour of th e coticule.

Th ough the garnet-bearing coticule has always been taken as a good proof of a high -grade metamorphism , I questioned thie idea, after Ifound at Beverce, near Malmedy, a typical coticule made if garn et, mica, chlorite and carbonate, in a hardly metamorphic enviromen t. The discovery of garnets in the Lienne-Valley where the metamorphism is as good as nothing, stress this point further.

That the spessartite develops through manganese, quite at the first steps of the metamorphism- if any - seems clear to me. Ialso pointed out earlier that the magnetite could be indicative of n o grade of metamorphism. In the Belgian regions, this is clear enough, but its widespread occurrence in some French iron-ores of the Lorraine district would still be more convincing.

Iregret that Iam not a member of the geological Society of London, but if you think that this letter could interest some members, you may show it at a next meeting, as a contribution to the discussion of May 20th.

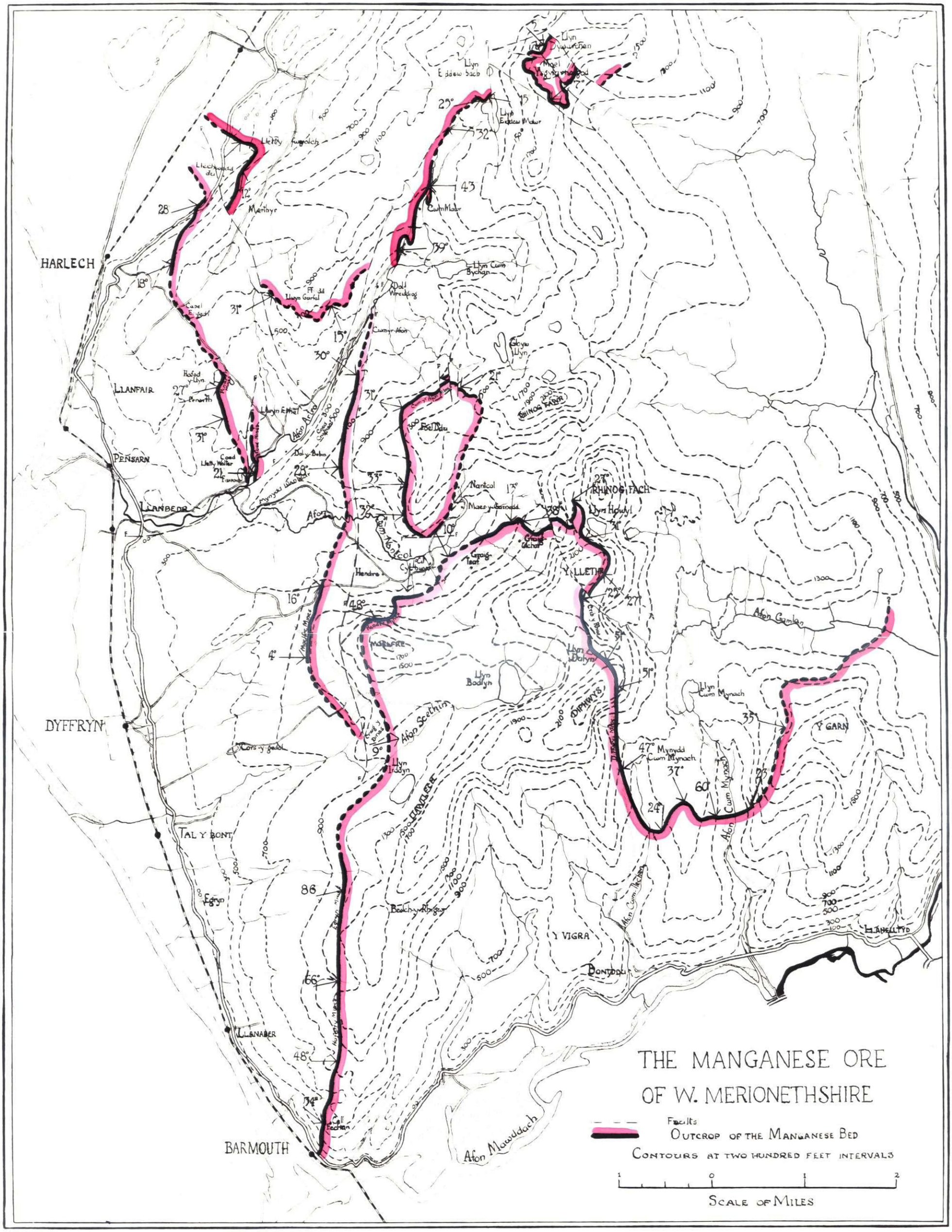
Hoping to meet you in the near future,

I remain,

Very sincerely yours,

F. Corin (Signed)
Geologists at the Belgian Survey,

Brussels.


HARLECH
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Llyn Cwm Bychan
Llyn Gwernan
Llyn Gwernfawr
Llyn Gwernddu
Llyn Hywel
Llyn Cwm Mynach
Llyn Bodlyn
Llyn Irddyn
Llyn Cwm Llechen
Llyn Cwm Nantcol
Llyn Cwm Mynach

The Petrography and Petrology of the Cambrian Manganese-bearing sediments of West Merionethshire (N. Wales).

SUMMARY.

The present work was undertaken to determine the nature and origin of the Manganese-ore bed, which occurs in the lower portion of the Manganese or Hafotty Shale Group of the Harlech Grit Series of West Merionethshire (North Wales). This has involved a detailed study of the associated sediments, which were all found to contain abnormal amounts of manganese. The deposits included grits, mudstones, pyrite-bearing rocks and sphaerodialogite developments.

The distribution of these rocks has been mapped on the 6 inch scale and an account of their field relationships is given, this leading to a statement on the structure of the area.

In the laboratory all the rock types were examined in thin section, and in addition the heavy mineral content of the grits was investigated. Chemical analyses of the ore-material and of the mudstones and sphaerodialogite rock were made, and from these the chemical composition of some of the minerals concerned have been obtained: green chlorite, indirectly, from analysis of sphaerodialogite rock; yellow-chlorite in the ore; and spessartite which makes up a large proportion of the ore.

The normal mudstones, together with the matrix of the grits, represent low grade metamorphic derivatives of an alumina-rich mud which contained much disseminated manganese carbonate. This type represents the chlorite zone of normal regional metamorphism. The presence of manganese carbonate led to the very early formation of spessartite, long before the appearance of any other minerals indicative of higher grades of metamorphism.

Certain mudstones are described, which represent more advanced stages of metamorphism, both the biotite- the garnet-zones being recognised.

Zones of fibrous authigenous minerals are recorded surrounding pyrite crystals in all the rocks, indicating that the genesis of the pyrite crystals post-dated the induration of the rocks in which they occur.

The manganese ore, consisting of dialogite and spessartite in approximately equal proportions is the metamorphic derivative of a deposit formed by the precipitation, within an enclosed basin, of manganese carbonate & clayey materials in a colloidal form.

THE PETROGRAPHY AND PETROLOGY OF THE CAMBRIAN MANGANESE-BEARING SEDIMENTS OF WEST MERIONETHSHIRE (NORTH WALES).

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INTRODUCTION AND HISTORY OF PREVIOUS RESEARCH.

INTRODUCTION AND HISTORY OF PREVIOUS RESEARCH.

The Cambrian manganese-ore of the Ardudwy district of Merionethshire occurs interstratified in that series of rocks which locally formsthe lowest Cambrian and is known as the Harlech Grit Series. This series crops out in a broad mountainous tract, the outline of which is an irregular oval, with the longer axis aligned north and south. It extends from Barmouth in the south to within about one mile of Ffestiniog on the north, and from the coast on the west to the Ganllwyd Valley on the east, thus occupying something over 100 square miles.

Ramsay[1] was the first to describe these beds, giving to them the term "Cambrian" and placing the fossiliferous Menevian beds above (now middle Cambrian) into the "Lower Silurian". He describes them thus:

"The rocks of this region principally consist of coarse quartzose, greenish-grey grits, the quartz grains being sometimes associated with interspersed granules of felspar. The rock has often a semi-crystalline aspect, perhaps due in most cases to the original angularity of its component grains, and in others to the partial effect of what is termed metamorphic action. The beds seem to have been formed partly from the direct waste of rocks of a granitic character, or at least into the composition of which quartz and crystalline felspar largely contributed. Occasionally the strata are conglomeratic, quartz, and more rarely felspar pebbles being disseminated in a gritty base. They are always hard and solid, and often very massive, attaining a thickness of 8, 10 or even 12 ft..... Sometimes they are purple and fine-grained, and they are intermingled with occasional bands of greyish-green and purple slates, which, especially towards the lower part of the series, attain a considerable development."

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1 Ramsay, A. C. Mem. Geol. Surv. Gt. Brit. The Geol. of North Wales. 2nd edition. 1881. p.19.

J. G. Goodchild[1], in 1893, grouped these rocks as follows:

1. Upper Mudstones (Lingula Flags and Menevian); Upper Manganese Bed at base.

2. Upper or Moelfre Grits.

3. Lower Mudstones: Lower Manganese Bed at base.

4. Lower Grits.

He thus recognized two manganese horizons separated by at least 850 ft. of rock.

Finally Charles Lepworth and Dr. T. Stacey Wilson[2] recognized only one manganese-ore horizon and divided the Harlech Grit Series of the Survey as follows:

1. Cefn or Llanbedr Slate Group: Blue or purple shales, flags and slates; to the west (Egryn, Llanfair) with occasional grit bands; to the east (Cefn Cwm, etc.) the grits are more abundant, and the lowest beds (Dolwen) are red felspathic grits and shales.

2. Rhinog Grits: Massive grits forming the Rhinog and other mountains; thickness about 2500 ft.

3. Hafotty or Manganese Shale Group (with the well known persistent zone of manganese ore at the base): Grey and green shales and flags; to the west with rare grits, to the east the grits become more frequent and eventually coarse and thick-bedded; total thickness about 1,000 ft.

4. Barmouth Grits: Massive felspathic grits or grey wackes with pebble beds, say 600 ft. thick

5. Gamlan Shale Group: A succession of grey, greyish-green and sometimes purple shales, slates and flags, interbedded with occasional grit bands, which increase in number and thickness on going eastwards; thickness 750 - 1,200 ft.

Evidence is brought forward (p. 20-1) that supports this interpretation of the succession employed, which was confirmed by field mapping of the Manganese Beds on the 6 inch scale.

The manganese-ore band occurs interstratified among the Hafotty or Manganese Shale Group (Lapworth and Wilson) about 30 ft. above the topmost massive grit of the Rhinog Grit Group. The actual ore is 10 - 18 inches thick and the pre-existing ideas concerning it can be summarised as follows:

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1 Dewey, H., and Dines H. G. Mem. Geol. Surv. Spec. Rep. Min. Resources of Gt. Brit. Vol.I. Tungsten and Manganese Ores, 3rd Edition. 1923. p.59, quote Goodchild, J.G.: MS six-inch Geological Maps, Merionethshire 26 N.W., S.E., 31 S.E; and 36 N.W., deposited in the Library of the Geological Survey.

2 Cited in Andrew, A. R. "The Geology of the Dolgelley Gold-Belt, North Wales." Geol. Mag. Dec.V. Vol.VII. 1910. p.161.

1881: Ramsay[1] allowed the manganese deposits to be mapped as lodes, at the same time remarking that they seemed to him "to be merely parts of softer strata impregnated with oxide of manganese in the line of strike, that is to say, at right angles to the dip of the Cambrian beds, as shown by arrows on the map".

1887: E. Halse[2] in describing an outcrop of the ore near Barmouth says: "The latter (manganese workings) are in no instance more than a few fathoms deep; the black oxide was found not to go down and the veins were at length abondoned. About fifteen months ago it was discovered that the deposits are really the outcrops of one and probably more beds of impure carbonate of manganese, which beds can be traced coming up to the surface at different points right away from Barmouth in the south to within two miles of Ffestiniog in the north".

In discussing the composition of the ore he states: "If the whole of the carbonic acid in the Welsh ore is taken up by protoxide of manganese, it contains 33 1/3 per cent of the carbonate; but doubtless there are present several units per cent of iron, magnesium and calcium carbonates. Mr. Holgate finds there is 4 per cent of silicate of manganese in the ore, the remaining protoxide and peroxide are probably combined together.

"The ore is a mechanical mixture and seems to be made up of about

30 per cent carbonate of manganese

4 " " silicate of manganese

40 " " oxides of manganese, iron as oxide (magnetite), carbonate, and sulphide (pyrites), magnesium carbonate, etc., and free silica.

26 " " clay"[3]

1910: W. G. Fearnsides[4] states:

"Above the grits (Rhinog Grits) are the much mixed manganese beds, fine sediments which may once have been limestones....."

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1 Ramsay, A. C. op. cit. p.65.

2 Halse, E. "On the occurrence of Manganese ore in the Cambrian rocks of Merionethshire." Trans. North of England Inst. Min. & Mech. Eng. Vol.XXXVI. 1887. p.104.

3 loc. cit. p.114.

4 Fearnsides, W.G. "North and Central Wales". Geology in the Field, London 1910. p.792.

1923: Dewey and Dines[1] in their memoir on Manganese state:

"The bed varies in thickness from ten to twenty inches, and is coated near the surface, and on the joints and cracks, with black oxide of manganese, a decomposition product, which containes from 20 to 32 per cent of metallic manganese. It is everywhere underlain by a bed of grit containing numerous cubes of iron pyrites."

"The manganese-ore consists of an outer weathered crust of hydrous oxides of manganese, and the mass of the bed which is composed of the mixed silicate and carbonate of manganese ..... The unweathered ore is a flinty-rock banded with various shades of pink, yellow and grey, known as the "hard rock".[2]

1927: Cox and Wells[3] describe the manganese band thus:

"Near the base of the group (Manganese shale) comes the persistent band of mangsnese ore, which is in the form of a laminated mudstone, obviously sedimentary in origin, and traceable at one and the same horizon over considerable areas. The ore bed varies from 10 to 20 inches in thickness and consists of alternations of dialogite (a manganese carbonate) and rhodonite (pink manganese silicate). The manganese content usually lies between 20 and 35 per cent. At the surface the ore oxidises to black pyrolusite".

T. C. Nicholas[4] found in the St. Tudwal's Peninsula of Caernarvonshire, an unfossiliferous series of rocks at the base of the Cambrian which he correlates directly with those of Merionethshire. The Mulfran Beds, lying between the Hell's Mouth Grits and the Cilan Grits are correlated directly with the lower part of the Hafotty or Manganese Shales of Merionethshire, and he states, "The lowest 50 ft. consist chiefly of sandy mudstones with occasional grit bands; they are the richest in manganese, and have been slightly quarried at intervals all along the cliff

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[1] Dewey and Dines: op. cit. p.60. [2] p.63.

[3] Cox, A. H., and Wells, A. K. "The Geology of the Dolgelley District, Merionethshire". Proc. Geol. Assoc. Vol.38. p.270. 1927.

[4] Nicholas, T. C. The Geology of the St. Tudwal's Peninsula (Caernarvonshire). Quart. Journ. Geol. Soc. Vol.71. 1915. p.

top." This horizon richest in manganese is correlated with the manganese band in Merionethshire, and the whole series is regarded as being the westward continuation of the Harlech Grit Series.

The present work includes a description of the distribution of the Cambrian Manganese-bearing rocks of West Merionethshire; a study of their petrography, chemistry and petrology, leading to a theory of their origin, formation and subsequent alteration, incorporating suggestions concerning the conditions in vogue at the time of their formation.

THE FIELD OCCURRENCE OF THE MANGANIFEROUS ROCKS OF THE HARLECH DOME.

The Field Occurrence of the Manganiferous Rocks in the Harlech Dome.

Following the succession employed by C. Lapworth and Stacey Wilson, it is found that the manganiferous rocks are confined largely to the lower portion of the Manganese (or Hafotty) Shale Group. These follow on the very massive, and for the most part very coarse, Rhinog Grit Group, which is at least 2,500 ft. thick.

The manganese ore, itself, is a band of an approximate uniform thickness, viz: 12 inches, and it keeps to a constant stratigraphical horizon, about 30 feet above the uppermost massive grit of the Rhinog Grit Group. The junction of the Rhinog Grit Group and the Manganese Shale Group is unmistakeable. The uppermost part of the Rhinog Grits consists of very thick massive grits, with no intercalated mudstones of note, and these give way very abruptly to a series of grey-blue, often quite well cleaved mudstones (the cleavage showing best on the weathered rock) which contain, for the most part, only very minor intercalations of grit. These are very uniform in character up to the manganese ore.

The manganese ore is a very hard, flinty rock, with no cleavage, no regular jointing, and with a sub-conchoidal fracture. It is of a sedimentary nature and is very well banded, the individual bands being pink, yellow, brown, and blue-black in colour. The rocks associated with the ore-band display a marked constancy of character over the whole area. They can be summarized as follows:

Below the ore-band and sometimes separated from it by an inch or two of dark grey-blue massive mudstone, occurs a band, usually an inch or two in thickness, of dark green mudstone with very abundant often large pyrite crystals, and abundant minute magnetite crystals. Beneath this occurs the normal blue-grey mudstones which separate the ore from the Rhinog Grits, and which are only very feebly manganiferous. These, when they have not been leached by prolonged exposure, weather a reddish-brown, though the colour is not as intense as in the Lingula Flags.

Immediately above the ore there follows 5 ft. 6 ins. to 6 ft. of mudstones of a remarkable character. They are blue-grey in colour and have a very regular lamination, the individual laminae averaging 1 - 2 mm. thick, of paler, blue-grey material and darker blue-grey material. These

contain occasional intercalated, very irregular layers of white carbonate material and often, in the lowest portion, immediately above the ore, have thin layers of material similar in character to that of the ore band itself. Usually there is but very little variation throughout the whole thickness of these striped mudstones. They are everywhere notably manganiferous in character and on weathering the surface takes on a blue-black colour which shows the striped banding of the rock particularly well as a regular alternation of dark, almost black, bands and slightly paler blue-black bands, the former corresponding to the lighter layers of the unweathered rock. This type of weathering is due to the development on the exposed surface of a thin film of finely divided pyrolusite by the alteration in situ of the manganese carbonate which the rock contains. Owing to its unique character this horizon of striped mudstones was given a special name by the miners - the "bluestone", a term originating apparently from the characteristic tint which the unweathered rock displays.

Above this comes a much more massive stratum, varying from 2 to 4 ft. This is everywhere coarser in grain than the "bluestone" but the degree of coarseness varies considerably. Often it is a coarse grit identical in appearance with the normal grits of the region, but sometimes it is merely a gritty mudstone with relatively infrequent small fragmental grains. However, when it has a fine-grained muddy character it is clearly marked off from the "bluestone" below by its more masive unbedded character. It contains manganese in small quantities and the weathering surface becomes coated with a thin film of blue-brown material (pyrolusite). For convenience, in later description), this gritty horizon is termed the "Bluestone Grit".

Following on this grit is a regularly banded mudstone not unlike the "bluestone" in its well-bedded character, but differing very noticeably by the absence of the very marked blue-black manganese weathering, and its manganese content, compared with that of the "bluestone", is very low. It is grey in colour and marks the oncoming of normal mudstones, similar to these below the ore. Above this the rest of the Manganese Shale Group consists of a sequence of grey and blue-grey mudstones and grits, with the former predominating.

Approximately 50 ft. above the ore horizon occurs 30 to 40 ft. of very massive grits with only occasional thin partings of mudstone. These grits can be traced over the whole area with only minor modifications. This will be referred to as the "Forty Feet Grit". The "manganiferous strata" for the purpose of this study include the succession of rocks from the pyritiferous mudstone immediately below the ore to the top of the "Bluestone Grit". This "section" has been carefully examined over the whole area, and in the following account of the distributional details attention will be practically confined to it. The map shows the outcrop of the manganese ore, which will be described as traced from south to north.

The manganiferous rocks are well exposed near the north entrance of St. John's Church, Barmouth. The section here is well exposed in a cutting and it was carefully measured. It extends well above the "Bluestone Grit" and all the details will be given as it gives a good idea of the general lithology of the Manganese Shale Group:

1. **Pyrite band:** green mudstone with abundant pyrite crystals - 3 inches.

2. **Manganese ore:** 11 - 12 inches thick.

3. "Bluestone".

   a. Thinly striped normal "bluestone", 5 ft. 6 inches. The lower 3 ft. 1 inch is quite normal in character; then occurs a thin gritty band, followed by normal striped mudstone, 5 inches thick, upon which rests a more massive mudstone band $6\frac{1}{2}$ inches. This is followed by $2\frac{1}{2}$ inches of striped mudstone and $1\frac{1}{2}$ inches of massive mudstone. The uppermost 13 inches are of normal "bluestone" character.

   b. Thin undulating layer ("ripple band") of sphaerodialogite, $\frac{1}{4}$ inch thick.

   c. Mudstone $\frac{1}{2}$ - $\frac{3}{4}$ inch thick.

4. "Bluestone Grit".

   a. Massive gritty band, very coarse at base; varies in thickness up to 6 inches.

   b. Mudstone, partly striped, but with much intercalated gritty material 8 inches.

   c. Grit $1\frac{1}{2}$ inches.

   d. Thinly bedded mudstone $6\frac{1}{2}$ inches.

   e. Thinly bedded striped mudstone grey in colour with a bit slightly marked manganese weathering 15 inches.

   f. Massive mudstone $2\frac{1}{2}$ inches.

   g. Thinly bedded mudstone 4 inches.

   h. Thick massive grit, 4 ft. thick with very coarse "conglomeratic" layer at base. Sometimes in the middle portion of this band are developed lenticles of a fine-grained mudstone material. These lenticles appear and disappear rapidly and vary from 1 to 2 ft. long and from 2 to 4 inches in thickness. Some large lenticles occur near the base of the grit and immediately above the "conglomeratic" layer. In the main the lenticular developments are orientated parallel to the bedding, but some cross it at approximately 45°.

5. Mudstone-Grit sequence. 30ft.

a. Dark compact mudstone with fairly well pronounced manganese weathering, 3 inches. The top four inches of the grit show the oncoming of mudstone conditions; it consists of an admixture of coarse gritty material and fine-grained mudstone.

b. Green compact gritty rock with "conglomeratic" base and containing irregular lenticles of mudstone - 18 inches. The grit is finer grained and the lenticles of mudstone more numerous in the upper portion.

c. Continuous mudstone layer 2 inches thick.

d. Pale grey, massive grit, 2 ft. thick with "conglomeratic" base, becoming finer upwards.

e. Fine-grained, dark-grey rock, with well marked thinly bedded lithology. Manganese weathering is absent. A layer of pyrite is irregularly developed at the base. 2 ft. 3 inches thick.

f. Massive gritty band, 1 ft. 3 inches thick.

g. Massive well banded mudstone similar to e. Very dark in colour. The individual layers are uniformly much thicker than in the "Bluestone". 8 ft. thick

h. Massive fine-grained grit, dark grey in colour, 12 inches thick.

i. Fine grained, well bedded, striped mudstone, the layers varying from 1/16 to 3/8 and rarely 1/2 inch in thickness. The weathered surface shows an alternation of dark iron-black and brown bands, 40 inches.

Upwards the same lithology is maintained up to the "Forty Feet Grit": an alternation of thinly bedded mudstones and occasional gritty bands up to 12 inches thick.

6. "Forty Foot Grit." — a succession of thick massive grits, approximately 40 feet thick.

Northwards from Barmouth the outcrop follows a line extending just north of Cell-Fechan through the Mines of Hafotty and Egryn, after which it is temporarily lost, before reaching the Afon Scethin, beneath the drift. At Cell-Fechan the section (generalized) was as follows:

1. Pyritiferous mudstone, 3 inches.
2. Manganese ore, 12 inches.
3. Bluestone 5 ft. 6 inches with "ripple band" near top.
4. "Bluestone Grit". a. Grit, 8 inches.
   b. Bluestone with frequent more gritty bands, 1 ft. 4 inches.
   c. Massive grit 4 ft.

In one portion of the Egryn outcrop the lithology is unusual. The ore has a reddish-brown colour, the banding is much crumpled and most of the associatel rocks have a reddish tinge. The "Bluestone Grit" horizon stands out clearly: a compact grit, 15 inches thick, follows the bluestone and is separated by a small thickness of mudstone from a massive grit 5 ft. thick, which is again separated from another grit 2 ft. thick by a thin layer of mudstone. All these grits assume a marked reddish colour on weathering. Some of the mudstones below show minor folding and also weather red. 100 yards north and 500 yards south of this locality the ore and the accompanying mudstones resume their normal character.

Northward the outcrop is inferred to cross the Scethin beneath the drift, and carrying on east of Craig-y-Dinas, ascends the western slopes of Moelfre to link up with the outcrop which is well seen in the Hendre Mines on the north and north west slopes of Moelfre. Here, apart from the unique development within a small area which is described on pp. the section through the manganiferous rocks is quite normal. The bluestone is 5 ft. 4 inches in thickness and the "Bluestone Grit" is well marked, being massive and 4 ft. 6 inches thick. The peculiarities noted here in the lower portion of the outcrop are discussed elsewhere in this thesis and the suggestion made that they are due to localized metamorphism and that originally the lithology was normal.

From these working the outcrop can be traced northwestward towards the bottom of the Nantcol Valley below Craig Isaf Farm, from which point it rises gradually to the locality where the ore has been mined again

well up the north-west slopes of Y Llethr and the south-west slopes of Rhinog Fach. Good sections are visible through the manganiferous section at the entrance to some of the drifts. Some 12 1/2 inches of uniformly fine-grained mudstone separate the green mudstone with pyrite from the base of the ore, the upper 3 1/2 inches showing transition to the ore band by the intercalation within the mudstone of thin layers of ore material. The manganese ore reaches the maximum proved throughout the whole area - 18 inches. The "Bluestone Grit" is merely a gritty mudstone, which can be distinguished from the normal "bluestone" by its massive character and the absence of marked manganese weathering. Upwards it passes into grey mudstone, whose bedding is not nearly so well marked as is that of the "bluestone", and which is not as manganiferous.

Some little distance down the valley side from these drifts, a massive greenish mudstone with scattered pyrite crystals lies immediately below the ore, which is 17 inches thick. In this locality 30 ft. of mudstone exists between the Rhinog Grits and the ore band, and the "Forty Feet Grit" occurs 30 - 35 ft. above the ore.

In the south east of the region the manganiferous horizon is proved on the eastern side of the Cwm Mynach Valley, one and a half miles north of the Dolgelley-Barmouth road. Here outcrop-workings extend a short distance up the valley side. The horizon can be traced along the western slopes of Y Garn, finally turning north eastwards before crossing the Afon Gamlan. Along this western slope of Y Garn no trace of the ore band was found and it appears to peter out in this direction. Evidence supporting the idea that the ore dies out eastward on these western slopes of Y Garn is forthcoming from the examination of the ore sections in the workings on the lower slopes. In the bottom-most workings the section through the ore horizon was as follows:

1. Whitish "poor", flinty manganiferous rock, 2 1/2 inches.
2. Manganese ore 6 1/2 inches.
3. "Bluestone", 2 1/4 inches.
4. Manganese ore, 2 inches.

Further east up the slopes of the valley side the corresponding section is:

1. Mudstone with thin bands and irregular globular masses of manganese ore material, $1\frac{1}{2}$ inches.

2. True ore, $5\frac{1}{2}$ inches.

3. Grey mudstone, not striped, $1\frac{3}{4}$ inches.

4. Manganese ore, 1 inch.

These two sections show the eastward attenuation of the ore band which is being replaced by mudstone, and suggest the ultimate disappearance of the ore somewhere on the western slopes of Y Garn.

The general lithology of the associated rocks is more or less normal. The pyrite layer is present, the "bluestone" has thinned eastward to 3 ft. 2 inches, the "Bluestone Grit" consists of two quite coarse massive grits 10 inches and 18 inches thick separated by 9 inches of striped mudstone, not as manganiferous as the normal mudstone. At the top of the "bluestone" and $\frac{1}{2}$ inch below the lower grit band occurs the thin undulating band of sphaerodialogite, which is therefore at precisely the same horizon as it was at Barmouth. The massive grits are 40 ft. above the ore, and the mudstones that intervene between these and the manganiferous horizon are more gritty than is usual, there being many intercalated grit bands 6 - 12 inches thick.

Westward the outcrop bends northwestward to the top of Mynydd Cwm Mynach, then turns southwestward as it descends the western slopes. Good sections are obtainable in the workings on the western slopes. Here the pyrite band passes into the ore through a transition zone of mudstone 5 inches thick, containing layers of ore material $\frac{1}{8}$ - $\frac{1}{4}$ inch in thickness. The manganese ore shows no thinning nor replacement by mudstone and is $12\frac{1}{2}$ inches thick. The "bluestone" is normal in character and thickness, 5 ft. 3 inches. The "Bluestone Grit" is massive but not very coarse in grain. It is 3 ft. 8 inches in thickness and can be readily distinguished from the "bluestone" by its more massive character, the absence of any striped banding, and the much less marked manganese weathering.

On crossing the Cwm-llechem stream the outcrop strikes northward along the western slopes of Diphwys, crossing the mountain on its north-east spur, four hundred ft. below the summit. Exposures are not good as the region has a thin covering of drift and most of the workings have

fallen in. The only variation from the ideal section is in the "Bluestone Grit". This is not coarse but can be readily distinguished from the "bluestone" by its massive unstriped character. Its compactness is plainly seen by the fact that it forms a very good roof to the open workings and levels. It is 3 ft. 11 inches thick. This is followed by 2 ft. 6 inches of practically normal "bluestone" upon which comes a massive grit 3 ft. 6 inches thick. 32 ft. of mudstones intervene between the ore and the Rhinog Grits. Along the ascent to the crest of the north east spur of Biphwys these mudstones have been weathered into a marked trench, which stands out well between the grits of the Rhinog Grits and those of the "Forty Foot Grit" above the ore, which are here about 50 ft. thick and situated about 45 ft. above the ore.

This portion of the outcrop is cut by several minor faults striking due E-W. The down-throw of all these faults is to the south and they give a western displacement of the outcrop of about 50 ft. on the north side of the faults.

The outcrop descends to the eastern banks of Llyn Dulyn near which the ore is proved by several trial levels. From here the outcrop strikes northward and after crossing the crest of Crib-y-Rhiw continues along the eastern slope of Y Llethr, several hundred feet below the summit, finally turning northwestward and descending the back wall of the corrie in which Llyn Perfeddau is situated. Near this point the workings on the S.W. side of Rhinog Fach commence and so the outcrop is linked up with that already described as a continuous line from Barmouth. Several minor strike faults, running approximately N.N.W.-S.S.E. intercept the beds west of Llyn Howyl.

On the north of the Nantcol stream, just above Cil Cychwyn Farm, the outcrop of the manganiferous horizon is again traceable in a series of open workings, which extend northward for about three-quarters of a mile, rising gradually to the western spur of Foel Ddu, where no mining has taken place. The outcrop then turns northeastwards to join with the open workings a mile and a quarter above Cwm-yr-Afon Farm. Thence the outcrop can be traced (by means of the clearly marked Rhinog Grits), turning sharply southward along the eastern side of the gutter formed by a

small stream descending towards Maes-y-Garnedd Farm. The outcrop finally links up with the western line. The extreme southern portion of this enclosed outcrop is cut out by a small E-W fault.

All the members of the manganiferous section are recognized. Near Cil Cychwyn the ore band is 14 1/2 inches thick, and the "Bluestone Grit" is very fine-grained and only 1 ft. 6 inches in thickness. Above Cwm-yr-Afon the ore is reduced to 11 inches and the "Bluestone Grit" is similar to that at Cil Cychwyn and contains scattered pyrites cubes.

The outcrop south of Foel Ddu is disturbed by several minor dip faults, which throws the outcrop backwards and forwards, the down-throws varying approximately from 10 to 75 ft. In the Cwm-yr-Afon portion of the outcrop, several dip faults occur close together, and an accompanying strike fault gives repetition of the ore band over a small area. The down-throw of these faults are only of relatively small dimensions.

Throughout this area the relationships of the manganiferous horizon to the Rhinog Grits below and the massive grit horizon above remain constant in thickness and character.

Three-quarters of a mile west of the Hendre Mines open workings running practically N-S for 1/2 mile, prove the presence of the ore horizon again. The dip is the same as in the Hendre outcrop, i.e. slight variations from an easterly direction. The repetition is caused by a large strike fault, the outcrop of which occurs about half way between the two outcrops of the manganiferous rocks and is marked in the field by outcrops of irregular quartz veining and crushed grits and mudstones impregnated with quartz. Southwards the outcrops pass beneath the thick masses of drift in the upper reaches of the Afon Scethin. Since this repetition does not occur south of the Scethin in the Egryn locality, it is presumed that the strike fault causing it dies out beneath the drift somewhere in the neighbourhood of the Scethin itself. Northward the outcrops pass under the drift which fills the bottom and southern slopes of the Nantcol Valley. To the north of the Nantcol, after crossing the crest of Mynydd Llanbedr, the same line of outcrop is presumably picked up in the workings which occur above Coed Dol-y-Bebin and Coed Crafnant. The manganiferous horizon strikes northward descending to the floor of the Artro Valley where it is cut out by the large fault running along the course

of the Artro. Since the dips here are identical with those of the western slopes of Foel Ddu, and there is no intermediate reversal, this line of outcrops marks a repetition of the Cil Cychwyn and Cwm yr Afon outcrops. The fault causing the repetition (which is, therefore, the same fault as that seen on the western slopes of Moelfre) is seen in outcrop as a fairly extensive crush zone with abundant quartz-veining. It is accompanied by minor anticlinal flexures in the mudstones immediately west of the fault (i.e. on the down-throw side).

In the Moelfre region the "bluestone" is normal in character and thickness, and the "Bluestone Grit" is as follows: a fine-grained grit taking on a mudstone character towards the top, 2 ft. 10 inches, is followed by a layer 1 ft. thick of very fine grit, upon which comes 2 inches of striped mudstone and a fine-grained grit 1 ft. 8 inches thick.

A major fault extends along the course of the Afon Artro, tending to keep to the south east side of the river. It extends from the coast inland and dies out just to the south of Cwm Mawr Farm, north of Llyn Cwm Bychan. The down-throw is to the north-west. Several other faults in the region to the north west serve to complicate the distribution of outcrops.

About 600 yds. W 15°S of Dol-y-Bebin Farm, near the river, the manganiferous horizon crops out again and the ore has been worked in a series of open workings. This outcrop extends southwards until it is cut out by the Artro fault. These are the Lletty Mines. Crossing the river it extends in a northerly direction towards Llwyn Ethel Farm (Coed Mines), where it is lost beneath the drift. In this locality the "Bluestone Grit" is 4 ft. thick and is separated by 11 inches of mudstone, from another grit 1 ft. 6 inches thick, above which are the normal bedded mudstones not rich in manganese. The ore was not seen "in situ" but thickness intervening between the grit and the pyritiferous horizon is 6 ft. 6 inches; consequently the "bluestone" is approximately normal thickness.

500 yds. to the west the manganiferous horizon is proved by several trial holes in the neighbourhood of the fishpond in Coed Lletty Walter. This outcrop can be traced northward to the Penarth Mines on the banks of Hafod y Llyn. This marks repetition of the Coed horizon to the east, and

the strike fault causing this repetition is proved in the west bank of the river about 20 yds. below the Lletty workings . This fault follows the river bed until it is cut out by the Artro fault where the river makes a right angle bend 400yds. from the confluence of the Artro with the Nantcol. The fault is marked by a crush zone, about 6 ft. wide, with quartz veining and silicification of the crushed rock. It is presumed that this fault dies out northward, the outcrop of the Coed and Lletty horizon dying out with it.

At Hafod y Llyn normal bluestone is followed by a grit 2 ft. thick having a striped mudstone development in the middle, followed by striped mudstone 1ft. 6 inches thick and another grit 2 ft. thick. 30 - 35 ft. of mudstone intervene between the ore band and the Rhinog Grits.

North-westward from Hafod y Llyn the outcrop follows the lane to Capel Engedi beyond which it turns northwards, descending to the main coast road at Llechwedd ddu, just over a mile north east of Harlech. On crossing the road the outcrop turns north-west and is lost beneath the deposit of the coastal plain. A mile further along the road the manganiferous horizon crops out again near Lletty'r-Fwyalch Farm, the outcrop taking a south-south-west course to a point just west of Merthyr Farm, where it is cut out by the fault which causes this repetition. The fault (Merthyr Fault) apparently dies out against the Artro Fault about a quarter of a mile s.s.w. of Pont Crafnant.

The ore again crops out in the region south of Ffridd Llwyn Gurfal Farm, and is cut off westward by the Merthyr Fault. This apparently is the direct continuation of the outcrop faulted out near Merthyr Farm. In this locality the rocks undulate slightly, the dip continually varying in direction between north east and north west, the general effect being that of a syncline pitching north. Eastward the outcrop is apparently faulted out by a fault, with a down-throw to the E. and aligned nearly parallel to the Artro Fault and joining it near Pont Crafnant. No good sections are obtainable in the Ffridd locality.

Half a mile north of Dol Wreiddiog Farm the ore horizon crops out just north of the junction of the roads to Cwm Bychan and Cwm Mawr. To the south, this outcrop is cut out again by the Artro fault, which is here dying

out rapidly northward into a gentle anticlinal fold. The fault itself is proved near the road junction by the extensive quartz-veining. The outcrop is traceable northward along the Cwm Mawr stream, disappearing beneath the drift in the upper reaches, and finally reappearing on the north-west banks of Llyn Eiddew Mawr. At the northern extremity of the lake, the outcrop is cut off eastward by a fault extending in a n.s. direction through Llyn Eiddew Mawr and on through Llyn Eiddew Bach to the north. The down-throw of this fault is to the west.

At Cwm Mawr the ore is 12 inches thick and the "bluestone" normal in character and 4 ft. 11 inches thick. The "Bluestone Grit" is very fine-grained, but not banded and above comes mudstone not as well striped nor as manganiferous as the "bluestone". At Llyn Eiddew Mawr the ore passes by transition into "bluestone" 4 ft. 4 inches thick, above which comes a fine-grained grit 8 1/2 inches thick, followed by "bluestone" type mudstone 12 inches and a massive slightly gritty mudstone 4 ft. thick. Normal massive mudstone succeeds this.

On the east side of Llyn Dywarchen, 1 mile to the north-east of Llyn Eiddew Mawr, the ore again crops out. To the north it is faulted out by a fault running north-west - south-east with a down-throw to the north-east. North of this fault no exposure of this outcrop exists owing to the presence of another fault aligned north-east - sputh-west with a down-throw to the north, the rocks dipping northwestwards in this locality. A minor fault throws back the outcrop slightly, on the south-east of Llyn Dywarchen, and from this point it follows approximately the same height along the south-west slopes of Moel Ysgyfarnogod, its course being interrupted by several minor faults with only small throws. At a point half a mile south-east of the summit the outcrop turns northward until it reaches the fault which caused its truncation to the north.

In the region east of the lake, the ore, 12 inches thick, is followed by 4 ft. 4 inches of bluestone, which is succeeded by a coarse grit 4 1/2 inches thick and mudstone with coarser bands 4 ft. 6 inches in thickness. Sometimes the grit thickens to 12 inches, apparently at the expense of the bluestone which is only 3 ft. 3 inches thick.

On the south-west slopes of Moel Ysgyfarnogod (300 yds. north-west of Llyn Ddu) the ore is 10 inches thick, the "bluestone" containing many gritty bands in the upper portion, is 3 ft. 9 inches thick, and the grit following is quite coarse and 1 ft. 5 inches thick. Only about 7 ft. of mudstones intervened between this grit and the very thick massive grit horizon which is usually 35 - 40 ft. above the ore. These massive grits are at least 60 - 70 ft. thick.

Thus over the entire area where these rocks occur, the characters of the ore, the pyrite band below, and the "bluestone" horizon above remain very constant. Only minor variations are noted in the lithology of the bluestone, e.g. in the Hendre locality, snf there the variations are due to relatively advanced metamorphism (68ff). The "Bluestone Grit" horizon varies considerably over the area, but these variations can be shown to be quite logical. The grit is coarsest in the south and south-east (i.e. in the Barmouth and west Cwm Mynach Valley localities), and northward and northwestward the grit becomes finer in grain towards Diphwys, Hendre, Cil Cychwyn, Cwm-yr-Afon, north-west of Y Llethr, and Cwm Mawr. In the Cil Cychwyn, Cwm-yr-Afon and Y Llethr localities the increased fineness in grain is accompanied by a thinning of the band, and the gritty horizon in these localities is only 15 - 18 inches thick. In the north and north-west, increasing coarseness is again noted, in the Llyn Dywarchen and Moel Ysgyfarnogod localities. Here also, accompanying this increasing coarseness, the grits above the ore have thickened remarkably at the expense of the mudstones. The "bluestone" has thinned from 5 ft. 6 inches to 4 ft. and sometimes less, and the mudstones above the "Bluestone Grit" instead of being 25 - 35 ft. are merely 6 ft. in thickness. Increasing coarseness is indicated to the north-west, the grit at Hafod y Llyn being quite coarse.

Thus the "Bluestone Grit" horizon indicates that the centre of the basin of deposition was approximately in the centre of the present area of outcrop of the rocks, i.e. in the Diphwys to west of Rhinog Fawr localities.

The ore band itself appears to die out eastward on Y Garn, while it undoubtedly dies out westward, since in the St. Tudwal's Peninsula of Carnarvonshire, for whereas the manganiferous horizon is undoubtedly present, the ore itself is entirely absent.[1] Its behaviour northward and southward remains unknown.

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[1] Nicholas, T.C. On the Geology of the St. Tudwal's Peninsula (Carnarvonshire). Q.J.G.S. LXXI.(1915). p.91.

On the existence of only one ore horizon.

Lapworth's and Stacey Wilson's interpretation of the succession of the Harlech Grits, in which only one ore horizon is recognized, is now generally accepted. The old idea (e.g. that held by Goodchild) was that there were two marked horizons separated by five to six hundred ft. of strata. E. Halse[1] states the reasons for believing in the existence of two beds:

"If there be but one bed, it is evident from an examination of of the dips that (a) the rocks are in places greatly contorted, or (b) the bed has been faulted at least once.

"(a) The horizontal sections published by the Geological Survey do not show any great contortions, nothing, for instance, at all resembling those of the Cambrian rocks of Carnarvonshire; and although there is in places evidence of no mean bending, the average dip of the outcrops is too low - being only about 35° - to account for their presence through contortion merely .

"(b) There must be at least one large fault. A glance at the map will show that the outcrop of the Moelfre Mine is most probably a continuation of that of Cwm-yr-Afon, two miles further north; and that the upper Moelfre, Y Foel Wen and Cwm Bychan outcrops are portions of one and the same bed. The dip of all these outcrops is to the east; therefore, if they are all parts of one and the same bed, there must be a north and south fault running a little west of Moelfre and Y Foel Wen for at least four and a half miles, and throwing the strata down to the west at least 880 yds. No evidence for such a fault has yet been discovered. This being so, and until evidence of such a fault be forthcoming it may be as well to refer to ..... two beds from five to six hundred ft. apart, the upper of which corresponds to the Llyn Cwm Mynach, Diphwys, Hafotty, Upper Moelfre, Y Foel Wen, Cwm Bychan, Llyn Eiddew Mawr and Harlech outcrops; and the lower to the Moelfre, Cwm-yr-Afon, Artro and minor outcrops between Harlech and Artro."

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[1] Halse, E. "On the occurrence of manganese ore in Cambrian rocks of Merionethshire." North of England Inst. Min. & Mech. Eng. Vol.XXXVI. (1886-7), p.105-6.

It thus appears that the evidence for ore at two horizons depends on the repetitions of the ore between the Coed Dol-y-Bebin and Coed Crafnant outcrops and the Cil Cychwyn-Cwm yr Afon localities, and between the Moelfre outcrops and the Hendre outcrops. In the regions between the two lines of outcrops a thick mudstone succession gives way suddenly to a thick grit succession which immediately underlies the eastern ore horizon. A fault, if such does occur, lies at the junction of these grits and mudstones. In the Moelfre locality this horizon is the scene of much quartz-veining and a silicification of what appears to be crushed grits and mudstones, but beyond this there is little evidence of faulting. Above Coed Crafnant and Dol-y-Bebin, the horizon is marked by much quartz-veining and crush zones. The mudstones to the west of this line also suffer minor contortions and buckling often associated with the down-throw side of large faults. In addition the mudstones immediately overlying the western ore horizon become thinner and the grits underlying the eastern horizon become thinner in a northward direction. Thus there is good evidence for the existence of a large fault, upon the absence of which depends the two-ore hypothesis. Northward and southward, where critical sections regarding this fault would be expected, the evidence fails. Northward the fault is truncated by the Artro fault and southward it apparently dies out beneath the drift of the Scethin.

If there were no fault one would expect the repetition of beds to occur south of the Scethin, where the Egryn Mines are continuous with the Hendre outcrops, since the dips are constant right to the coast. There is, however, no evidence for such a repetition in this locality. Finally the general sequence from the top of the Rhinog Grits to the top of the "Bluestone Grit" is maintained over the whole area, in regions where both the "upper bed" and "lower bed" have been stated to occur. Moreover the structure of the area can be worked out on the assumption that only one bed is present.

Structure of the Area.

The general structure of the Harlech Dome can be seen fairly clearly from the study of the behaviour of the manganiferous horizon. From the map it is seen that it consists essentially of two major

anticlines and a central syncline. The major portion of the eastern limb of the eastern anticline is faulted out by the north-south fault extending along the Ganllwyd Valley through Trawsfynydd towards Ffestiniog. In the south the anticline pitches quite sharply in a southerly direction. Here Y Garn forms its eastern limb, and Llyn Cwm Mynach and Mynydd Cwm Mynach lie on its axis. On the western limb, or the eastern limb of the central syncline dips are from 20° - 60° and 25° - 50° on the western limb of the syncline. In the south, most of the western anticline is truncated by the coast, only in the extreme north-west, in the Llechwedd locality, is there any suggestion of the real crest of this anticline. Therefore, what really is seen is the western limb of the central syncline rising towards a western anticline. The central syncline becomes more conspicuous southward, and in the region between Y Vigra and Llawllech all the higher beds up to the Lingula Flags appear. As its axis rises northward the syncline becomes less well marked. The enclosed outcrop of the ore horizon from Cil Cychwyn to the Cwm-yr-Afon Mines marks it as a trough pitching south, but north-west of the Cwm Mawr Valley it begins to disappear owing to the oncoming of the northward pitch and in the extreme north, north and west of the Llyn Eiddew-Llyn Dywarchen region it has practically disappeared. Here the rocks dip steadily north and northwestward beneath the higher Cambrian beds of the Ffestiniog-Maentwrog region.

The eastern limb of the western anticline has suffered much collapse, a feature now shown by the number of large strike faults which traverse the north-west quadrant of the area. The centre of collapse seems to be marked by the Artro Fault. This, with the Merthyr Fault, gives the area of maximum collapse as towards the lower half of the Artro Valley. The other large faults give down-throws on the side facing the Artro Fault. Thus the Moelfre Fault has a down-throw to the west, and the Gerddi Fault, which truncates the Ffridd Llwyn Gurfal outcrop on the east, has a down-throw to the E. Thus the central elevated portion of the "dome" appears to have suffered collapse, probably during the initial folding of the region, the maximum collapse being in the central area. The main faulting dies out south and north: The Moelfre Fault near the Soethin, the Artro Fault near Cwm Mawr and the Gerddi Fault east of Moel

y Gerddi. These major faults approximate to a N-S alignment, i.e. they are nearly parallel to the main axes of the folding.

Minor faults occur over the whole area. They are mostly dip faults with down-throws of mere tens of feet. These are seen on Diphwys, Y Foel Ddu, Cwm-yr-Afon Mines and Y Llethr. The minor strike faults are best seen in the Moel Ysgyfarnogod region,(where vagueries of dip often make them appear as dip faults) and the Coed Lletty and Penarth region of the Artro Valley.

In the following sections of this thesis, the petrography and petrology of the associated manganiferous rocks are described. Attention is more or less confined to the rocks of the "section" described in detail above, i.e. the rocks between the pyritiferous layer below the ore up to the "Bluestone Grit". These include the grits, the mudstones, the pyritiferous rocks and the ore itself, and a separate section is devoted to each. In addition, the "ripple band" in the "bluestone" of Barmouth and the western side of the Cwm Mynach Valley was sufficiently unique to deserve a separate section.

Regarding the grits, attention is largely confined to the "Bluestone Grit" horizon in order that the variations of one grit horizon could be examined over the whole area. Examination of a number of grits from other horizons, including the Rhinog and Barmouth Grits proves that the grits throughout the Harlech Series show certain characteristic similarities in lithology. The mudstones also bear comparison with those of other horizons and so the examination of these rocks serves as a guide to the Lower Cambrian petrography of this area generally.

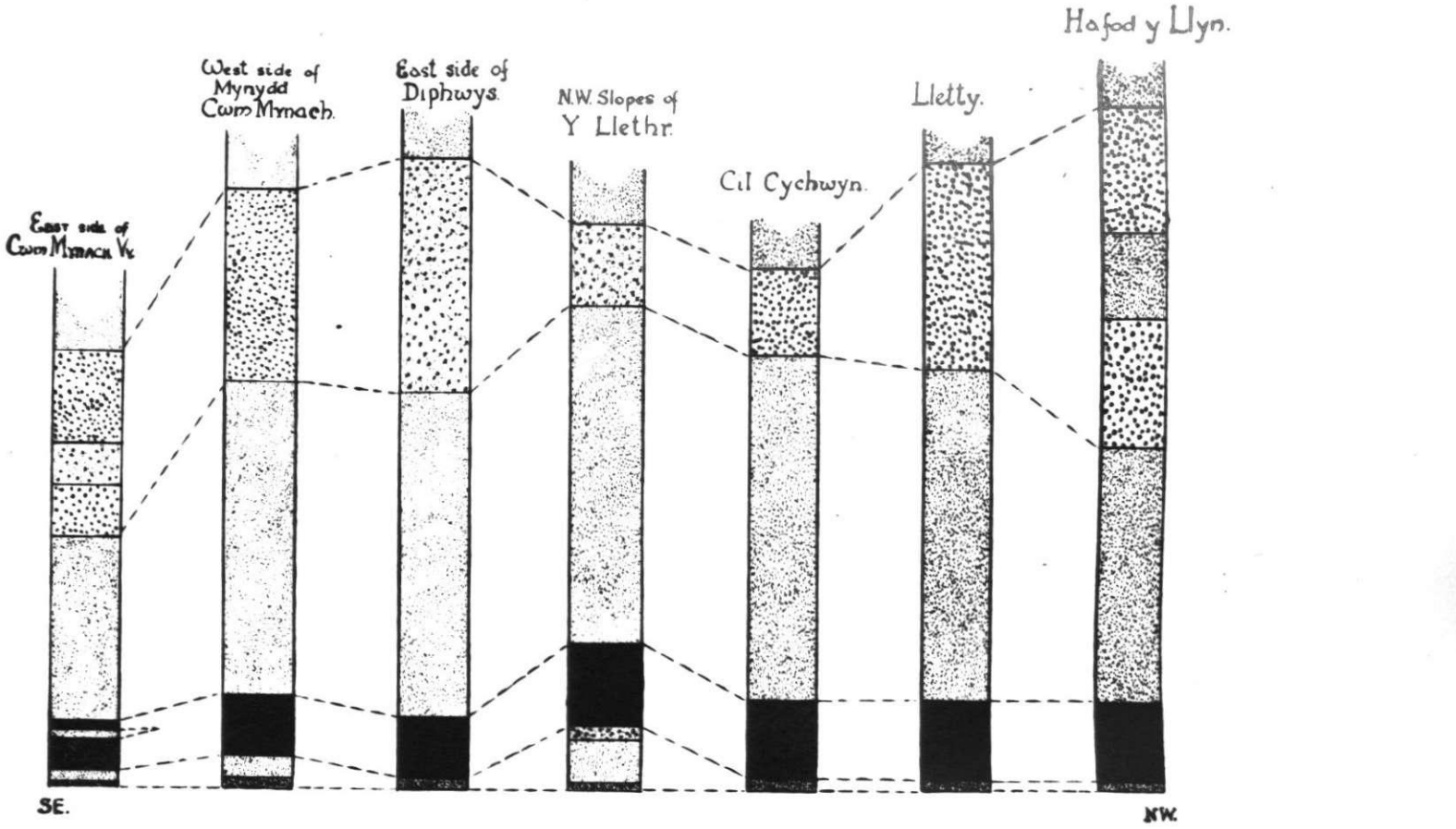


DIAGRAM TO SHOW THE LATERAL VARIATION IN THE SUCCESSION FROM THE BASE OF THE MANGANESE ORE TO THE TOP OF THE BLUESTONE GRIT.

The Grits Associated with the Manganiferous Rocks.

The grits which occur intercalated with these sediments have similar lithological characters. In the field they are very persistent laterally and can be traced over large areas. One such grit horizon, the "Bluestone Grit", about 5 ft. 6 inches to 6 ft. above the top of the manganese ore band, was proved to be present throughout the area and the petrography of this has been investigated in detail. Consistent variations in grain size, etc. take place throughout the region, but an examination of the variations within this one band is virtually an examination of the variations in all the grits. To show this similarity in type, one grit from a different horizon (No.18 in table) will be described petrographically and the heavy mineral content of this and another (No.19) has been investigated. For the sake of comparison, three samples of Rhinog Grit were examined, and the heavy mineral composition of these is given in the table.

Petrography of the Grits.

I. The coarser-grained grits.

A typical rather coarse grit (No.6) from the base of the massive "Bluestone Grit" immediately above the sphaerodialogite "ripple" band, on the east side of Mynydd Cwm Mynach shows the following characters:

Macroscopic Characters: A fairly coarse thickly bedded greyish-green grit, the average size of the individual grains of which is in the neighbourhood of 1 mm. Only quartz is recognizable, this varying from colourless to a variety possessing a distinct purple tinge. The grit follows very abruptly on a thin layer of mudstone, below which occur the thin contorted band of sphaerodialogite. The junction of the grit with the mudstone approximates to a true plane surface. When the grit powder was tested with dilute HCl, there was but little effervescence of CO_2 so that only a little manganese carbonate can now exist in the rock, a fact which is also borne out by the not very intense black colour which the surface of the grit takes on weathering.

Microscopic Characters: The grit consists of angular and subangular fragmental grains, consisting chiefly of quartz with very subordinate felspar, set irregularly in a matrix consisting chiefly of chlorite, throughout which are scattered very small spessartite garnets. The proportion, by volume, of larger scale fragmetal ma'erial to matrix is approximately 1 : 1.

The fragmental grains have the following characters: quartz is practically all of the clear transparent type with very minute opaque and globular gas-filled inclusions. Occasional grains show undulose extinction, but these in ordinary light are indistinguishable from the normal type. The felspars are subordinate, the predominant type being a very much decomposed orthoclase. Some fragments of decomposed material were originally plagioclase. (Original orthoclase and original plagioclase are distinguished by the different types of decomposition they now show, the former being "kaolinised" and the latter "saussuritised".) Occasional small, remarkably fresh, lamellar twinned plagioclase felspars occur; this is mainly of one type, with an extinction of 10 - 14° and is oligoclase. Among the rarer fragmental grains, and much smaller in size are recognized pale green,

somewhat rounded, epidote, rare muscovite, and zircon. The muscovite usually occurs as colourless cleavage plates. The quartz and felspar grains tend towards the same size, varying between 0.10 mm. and 1.4 mm., being on an average 0.6 - 0.8 mm. Although the felspars tend to show a more rounded outline than the quartz, they are regarded as being of the same derivation; the decomposing felspars would be sufficiently softer than the quartz to yield more readily to the degrading processes of rolling, etc.

The Matrix: this material was laid down contemporaneously with the larger fragmental material between which it formed an excellent packing material. As will be shown, it was of such a fine grained hydrated nature as itself to form the cementing material of the rock upon consolidation and induration. The matrix now consists of an intimate mixture of fibrous chlorite, fibrous sericite, and very minute quartz grains, and throughout this are uniformly scattered numerous small colourless garnets.

The chloritic and sericitic materials are commonly very intimately associated (as for example by the interlocking of the fibres of the two minerals), although in places more or less selectively developed chlorite or sericite occur separately in small patches. All the chlorite is apparently of the same variety and has a pale, though bright, green colour, and a distinct pleochroism from almost colourless or very pale green to bright green. The fibrous crystals tend usually to be rather stumpy. The sericite occurs in colourless fibrous crystals, having a somewhat higher birefringence than the chlorite. There is a distinct tendency for the fibres to be orientated at right angles to the fragmental grains, while away from the margins of these grains the fibrous crystals are arranged quite hapharzardly. The quartzose material is of a clear type, free from inclusions and has a minutely granular to almost fibrous character and is usually intimately mingled with the chlorite-sericite material. Sometimes it is localised into small patches of clear silica, which in polarized light give a granular undulose extinction, not unlike that of chalcedony. This quartzose material may represent very fine-grained detritus, but the freedom from inclusions, their irregular margins, and complete merging with the chlorite, with the mosaic character when developed in bulk indicate the chalcedonic variety formed from originally colloidal silica.

The small colourless garnets occur scattered more or less uniformly throughout the whole matrix. They vary in size from 0.006 mm. to 0.025 mm,

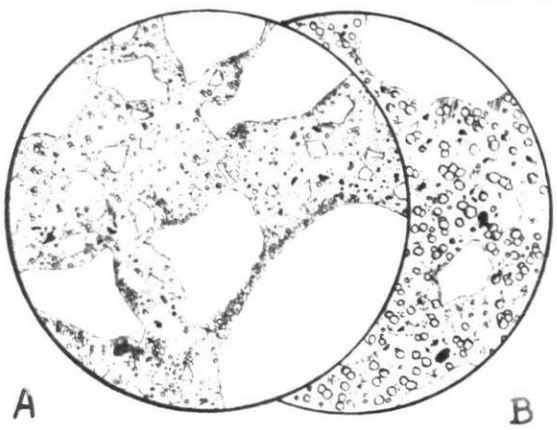


Fig. 1. "Bluestone Grit"; East side of Cem Mynach Valley.

A. Angular quartz fragments are set in a very fine-grained matrix of quartz-chlorite-sericite-garnet material. The small globular garnets stand out amongst the matrix. The chlorite laths tend to be orientated normally to the edges of the fragmental grains. Magnification x 30 diams.

B. The matrix, showing the relationships of the colourless spessartite garnets. Magnification x 100 diams.

being on an average 0.015 mm. to 0.018 mm. The smaller ones appear to have a spherical form, but many of the larger ones possess a good hexagonal outline and the constant recurrence of this hexagonal outline suggests the rhombododecahedron. They have a high refractive index and stand out very clearly (Fig.1). On account of their small size, individuals seldom extend throughout the thickness of the section, and as they are enveloped in non-isotropic material, they themselves appear to be non-isotropic. Careful examination of the larger grains, especially on the edges of the section, reveals their true isotropic character, and they are unhesitatingly referred to the garnet group. On an average these garnets make up about 10 per cent of the matrix material. Occasionally, however, e.g. Fig.6 they have developed to the virtual exclusion of other material and they appear as masses with an irregular honeycomb structure, the garnets being crowded one against the other. Under the low powers of the microscope, these masses often have the appearance of composite detrital grains, since the developments end quite abruptly against the normal matrix material. Under higher powers, however, the individuals of these masses are clearly the same as the garnets uniformly scattered throughout the matrix material, and the appearance of detrital composite grains is proved to be deceptive, because the masses can then be seen to be elongated, irregular, and with outlines depending on the shape and position of adjoining detrital grains. The garnets in these compact masses average 0.015 mm. and although the mass consists almost entirely of garnet, each individual still possesses a sufficient veneer of non-isotropic material to destroy the isotropic character of the garnets themselves.

Also scattered throughout the matrix are small crystals of a reddish-brown colour. These are semi-transparent and occur in very small crystals (0.005 mm. to 0.015 mm., averaging 0.010 mm.), having usually a hexagonal outline, sometimes regular and sometimes, with two opposite sides, somewhat elongated. They appear to be rhombohedra. They are not as abundant as the colourless garnets and often tend to occur concentrated in "nests". Owing to their minute size, their behaviour between crossed nicols is deceptive, but individuals isolated on the margins of the section are isotropic. They are, therefore, referred to the garnet group, and are assumed to differ from the colourless form in that the almandine molecule is

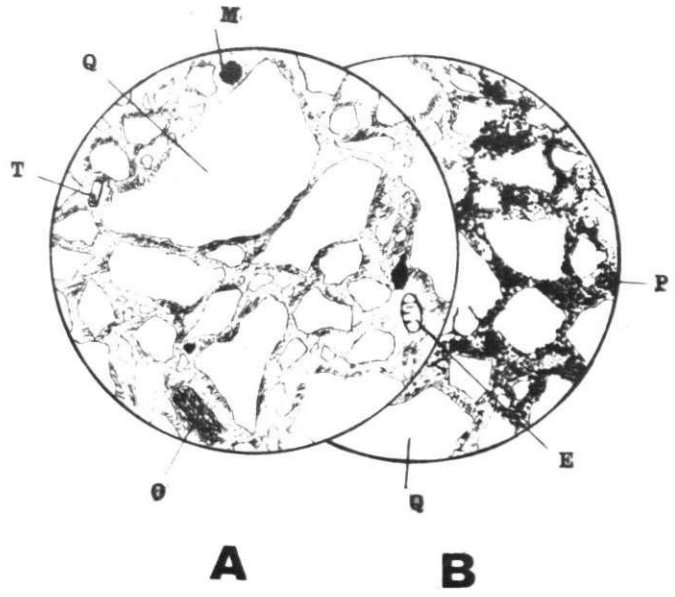


Fig.2 "Bluestone Grit"; East side of Llyn Dywarchen. x 30 diams.

A. General aspect of grit. Angular quartz fragments (Q), sub-angular felspar fragments (O), with occasional epidote (E), tourmaline (T), and magnetite (M) grains are set in a fine-grained matrix of dialogite, silica and chlorite.

B. The same to show the mode of formation of pyrolusite (P) by decomposition of the dialogite of the matrix on weathering.

predominant. This occurrence of two forms, one predominantly spessartite, and the other predominantly almandine, occurring together under the same conditions, of the same size, and clearly of the same order of derivation, would seem to indicate somewhat incomplete miscibility of the spessartite and almandine molecule under certain conditions.

Associated with these reddish garnets are small grains of opaque black material, referred to magnetite.

Throughout the matrix, and not abundant, occurs a colourless material, giving with polarized light, interference tints of very high order. This is manganese carbonate (dialogite).

A rather coarse grit (No.17) from the lower part of the "Bluestone Grit" horizon, E. side of Llyn Dywarchen, is darker in colour than the above and has a much darker colour on weathering. Microscopically, the rock consists of angular detrital fragments set in a much finer largely authigenic matrix (Fig. 2). The detrital fragments: Quartz is by far the most abundant. One type prevails: a clear colourless variety with minute opaque and gas-filled inclusions. The grains are very irregular and varied in shape, being on the whole very angular. Some composite quartz fragments are observed between crossed nicols, and a few fragments give true undulose extinction. Grain size: 0.10 mm. to 1.0 mm. averaging 0.35 mm. - 0.45 mm. Felspar grains have invariably suffered some degree of "kaolinisation" and they appear as dirty grey fragments, the smaller ones are often difficult to distinguish from the fine-grained matrix which encloses them. A few small fragments of plagioclase are present. These show, usually, no alteration, and they are only distinguished from the quartz by the lamellar twinning observed between crossed nicols. They have an extinction of about 10°: oligoclase. The felspars again tend to be more rounded than the quartz grains and vary in size from 0.2 mm. to 0.3 mm. Rare small angular flakes of colourless muscovite are present, averaging about 0.10 mm. Epidote: a few somewhat rounded grains of pale green epidote are observed. These show an irregular cracking, high polarization colours, and an extinction nearly straight; about 0.10 mm. Rare rounded grains of greenish brown tourmaline, showing intense pleochroism are observed; 0.07 - 0.15 mm. Occasional zircon crystals are seen under the high power. Frequent opaque fragments occur; chiefly allothigenous and authigenous

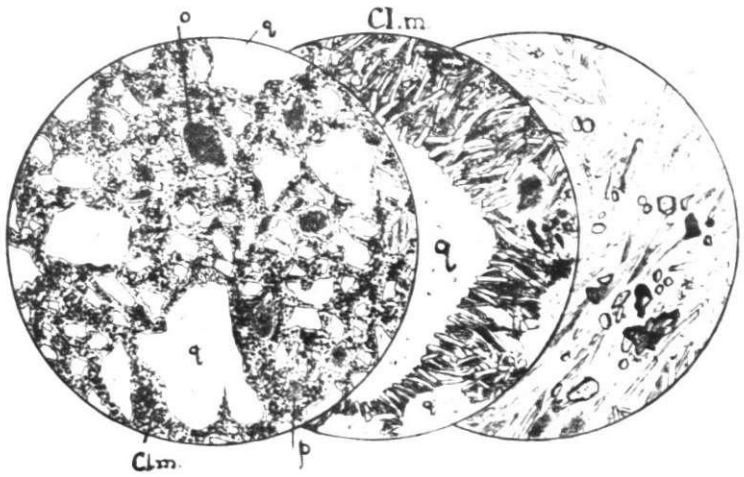
magnetite with some pyrite; 0.10 mm. - 0.20 mm.

The Matrix: This is uniformly very fine-grained and consists of an admixture of carbonate material, siliceous material (chalcedonic ?), fibrous chlorite and occasional fibrous sericitic material. The carbonate (which from the weathering is seen to be chiefly dialogite) is mainly of a granular nature, while the silica shows the fine undulose type of extinction, not unlike that of chalcedony. The chlorite fibres tend to be orientated in the same direction, in a plane parallel to the bedding, with a tendency to diversion towards a radial development with regard to the fragmental grains which they surround. There is a tendency for the chloritic and sericitic material to form a film enclosing the fragmental grains, and for the carbonate and the silica to occupy the spaces remaining. Within the matrix small reddish garnets are to be observed similar to those described above, but the colourless garnets are absent.

Weathering. The fragmental grains remain unchanged, but the matrix shows chemical and mineralogical changes. The chief of these is the decarbonation of the dialogite, leaving in its place an opaque, black material, in granular masses, which quite clearly indicate the original granular character of the carbonate (Fig. 2B). This black mineral is pyrolusite. Where this material adjoins quartz fragments, it has been absorbed along cracks. The silica has remained unchanged except for a tendency to become stained by the other products of decomposition. The chloritic material changes in colour from pale green to a golden yellow, finally becoming brown, a change probably due to the formation of very finely divided pyrolusite.

A massive grit, 25 ft. above top of ore (St. John's Church, Barmouth), is green-grey in colour, with the individual grains of quartz visible to the naked eye as irregularly sub-angular vitreous particles up to 3 mm. in diameter, set in a greenish-grey fine-grained matrix. Felspar grains, about the same size as the quartz grains, are distinguishable by virtue of their whiter colour.

Under the microscope the rock is seen to be composed of angular to subangular fragments of quartz and felspar, the former being more angular than the latter, cemented together by a much finer-grained material, now composed mainly of chlorite. (Fig. 3.)



A B C

Fig. 3 Grit, St. John's Church, Barmouth.

A. General aspect of grit showing the angular fragments of quartz and felspar set in a chloritic matrix. The quartz grains are more angular than the felspar. Magnification x 20 diams.

B. The fibres of chlorite and sericite in the matrix tend to be developed at right angles to the detrital grains. Magnification x 100 diams.

C. Small hexagonal reddish-brown garnets occur localised in "nests" in the chlorite matrix. Magnification x 30 diams.

q: quartz; p: oligoclase; o: orthoclase; f; felspar; Cl.m: chloritic matrix.

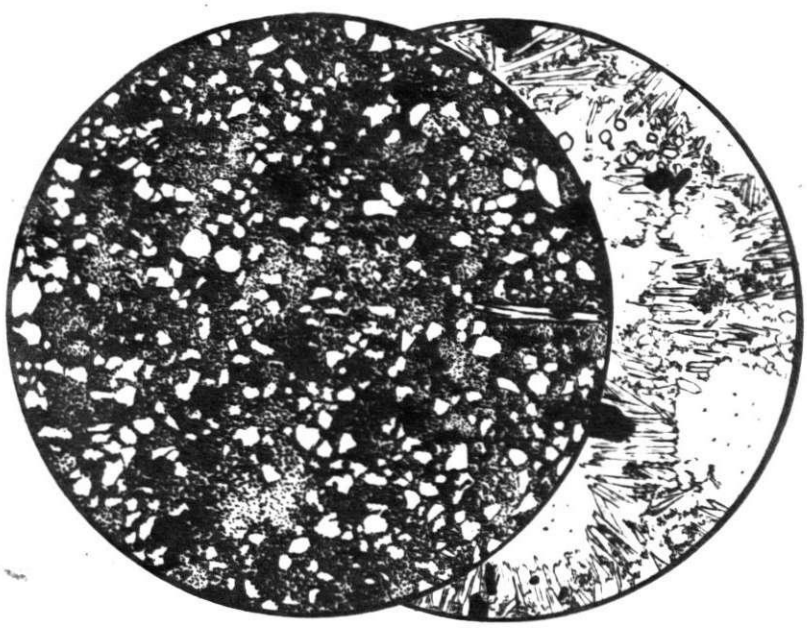
The quartz grains vary in size from 0.10 mm. to 1.0 mm. and are on an average 0.35 to 0.40 mm. They are chiefly of one type and are very irregular in shape. The predominant variety is transparent, colourless, with opaque and gas filled inclusions.

The felspar grains vary in size from 0.1 mm. to 1 mm., averaging .35 mm. Nearly all exhibit "kaolinisation", giving a dirty grey colour in ordinary light. Some possess a well-marked cleavage, with parallel extinction (orthoclase). A few small angular, unaltered grains of oligoclase occur. These average about 0.12 mm. Some fragments of "saussurite" material are regarded as having been derived from plagioclase. The ratio of quartz to felspar is approximately 20 : 1. Occasional grains of zircon, tourmaline, and epidote are observed.

The intergranular spaces average 0.05 mm. to 0.10 mm. wide. The matrix filling these interstices is of a uniform type. consisting for the most part of fibrous and irregularly radiating chlorite. The individual fibres are rather stumpy. They are green in colour and show a well marked pleochroism : pale green to bright green, the greatest absorption being parallel to the direction of vibration of the lower nicol. They sow the characteristic dull blue polarization colours. Intermingled with this chlorite, although not as abundant, occurs sericite. Its habit is similar to that of the chlorite. It is colourless and in polarized light shows high order colours. On the margins of the detrital fragments the intermingled fibres of chlorite and sericite tend to be developed with their long axes at right angles to the margin of the fragment. (Fig. 3a). This together with their wholly recrystallized nature show that both the chlorite and the sericite are authigenous.

Colourless garnets occur scattered throughout, but they are not very common. Their characters are exactly similar to those described above. They are best examined under oil immersion. The small, reddish-brown garnets with hexagonal outlines also occur. The same localisation in "nests" is noted. They are approximately 0.01 mm. in size, though some are larger and show very minute transparent inclusions (Fig. 3c).

There is slight effervescence when the rock is treated with dilute HCl, but as no carbonate is readily distinguishable it must occur in a very finely disseminated state. Since the weathered surface of the grit is of



A B

Fig. 4 "Bluestone Grit"; Cil Cychwyn, Nantcol.

A. General aspect of grit showing angular and sub-angular fragments of quartz and opaque minerals set in a much finer grained matrix, with rare flakes of white mica. Magnification, x 40 diams.

B. The matrix of the grit is a fine intergrowth of lath shaped chlorite crystals with silica, with interspersed "nests" of minute reddish-brown garnets. Magnification x 40 diams.

blue-black colour, so it is assumed that the finely disseminated carbonate is dialogite.

II. Fine-grained Grits.

Fine-grained grit (No.12): from the massive "Bluestone Grit" horizon on the slopes, west of Cil Cychwyn Farm, Cwm Nantcol.

Macroscopic Characters. A fine-grained gritty rock, somewhat cleaved. It is rather massive and shows none of the fine closely-packed banding of the "bluestone" which occurs below. Very small fragmental grains can be made out by the eye, and with the aid of a lens these can be seen to consist of quartz fragments and pyrite crystals. The latter often stand out as points of reflected light. The major portion of the rock consists of material of silt grade. Its colour is bluish grey. On weathering the surface becomes covered with a thin veneer of bluish-brown material showing faint manganiferous tendencies.

Microscopic Characters. The rock consists of angular and subangular fragments of quartz and felspar set in a matrix of much finer grade (Fig.4) The fragmental grains fall into two classes according to size. These for the most part consist of small angular and subangular fragments (0.06 mm. to 0.12 mm. and averaging 0.08 mm. in size) set uniformly amongst the much finer grained packing material. Among these are scattered haphazardly fragments much larger in size (0.3 mm. to 1.0 mm. and averaging 0.4 mm.). The detrital grains consist chiefly of quartz and among the felspars orthoclase is predominant.

The large quartz fragments consist practically entirely of the same type: clear, colourless, with minute opaque and gas- or liquid-inclusions and is similar to that occurring in the grits already described. The felspars are practically all very decomposed.

The smaller fragments consist chiefly (90 - 95 per cent) of quartz of the same predominant type. Orthoclase and decomposed plagioclase are observed, and grains of relatively fresh oligoclase are occasionally noted. The matrix which has recrystallized has eaten slightly into the surface of these grains and their margins are not clearly marked (Fig.4B). Very occasional fragments of colourless garnet are observed. These are irregular in shape and clearly detrital. They average 0.08 mm. to 0.10 mm. in size and do not show the regular spherical or hexagonal forms

that characterizes the smaller authigenic garnets.

The opaque minerals are abundant and form up to about 5 p.c. of the rock. They consist of about equal quantities of magnetite (with ilmenite) and pyrite. The former occurs chiefly as very irregular fragments and aggregates of small fragments (0.03 mm. to 0.08 mm.) and the latter as cubes (0.06 mm. to 0.12 mm. and sometimes larger).

The matrix consists essentially of an intimate mixture of pale green chlorite and quartz, both minerals having essentially the same characters as already described. A certain amount of sericite is also observed. Scattered throughout occur the usual minute reddish-brown garnets.

On weathering the chlorite of the matrix undergoes change, while on the surface of the much weathered rock pyrolusite can be detected, though not in large quantity. The chlorite on weathering takes on a yellow colour and it becomes non-pleochroic, and tends to lose its fibrous character. This has a lower refractive index than the chlorite, and the birefringence still remains very low. The nature of this change is correlated with the presence of the very small amount of manganese present.

A fine-grained grit from the Cwm-yr-Afon Mines (No.14), again from the "Bluestone Grit" horizon has the following characters:

A fine-grained blue-grey grit, containing larger grains of detrital quartz up to 1.5 mm. scattered irregularly throughout. Also haphazardly distributed throughout occur relatively large crystals (1.5 mm. - 2 mm.) of pyrite. The rock is slightly cleaved. On weathering the fine-grained matrix takes on a purplish-blue tint indicating the separation of pyrolusite, finely divided.

Microscopically it consists essentially of fragmental quartz, with subordinate felspar (grain size: 0.045 mm. - 0.15 mm., average 0.07 mm.) set in a matrix consisting of an intimate intergrowth of siliceous material, chloritic material and sericitic material with silica greater than chlorite, and chlorite greater than sericite. Scattered sporadically throughout are quartz and felspar grains of a larger grade (0.25 mm. - 1.0 mm., average 0.35 mm.) with felspar again subordinate. The fragments are subangular to sub-rounded, with those of smaller grade distinctly more rounded than those of larger grade. The quartz as in the previous grits is predominantly of a fresh colourless variety with minute opaque and gas or

liquid inclusions. Occasional composite quartz fragments and rare fine-grained composite quartzose fragments, which may be fragmentary fine-grained quartzite, also occur. Felspar fragments are rare, and are similar to those described in the previous grits.

Subordinate detrital minerals are: white mica, as platy wisps; brown tourmaline (.05 mm.); epidote (0.07 mm.); zircon (.03 mm. - .06 mm.); and irregular masses of magnetite (0.04 mm. - 0.06 mm.). These are all scattered irregularly throughout.

The matrix consists of an intimate intergrowth of quartzose material, chlorite and sericite. The texture is governed by the crystals of chlorite and sericite which are elongate lath-shaped, and the quartz has an apparent interstitial relationship to these. The grain size is approximately 0.005 mm. The quartz is colourless, practically free from inclusions and has no crystal shapes. The chlorite occurs as fibrous masses and as individual lath-shaped crystals (0.005 mm. long). In characters the chlorite crystals are identical with those described above. Scattered throughout are areas where only chlorite has developed; this is bright green, and the interlocking of the lath-shaped crystals has given a fibrous appearance. The chlorite has a somewhat higher refractive index than the quartz. The sericite is subordinate and occurs as fibrous and lath-shaped developments with the usual characteristics.

Rare colourless garnets identical with those already described occur. Their general infrequency indicates a low original dialogite content. Occasionally, these garnets are developed in small masses of a massive character, identical with those described earlier in this section. This indicates that the manganese carbonate was locally concentrated in small clots originally. The small reddish garnets also occur.

Very rarely there occur small "nests" of prismatic crystals. These are colourless, about 0.015 mm. long and 0.001 mm. wide, with an average length : breadth ratio approximately 15 : 1. They have pyramidal terminations. Their refractive index is high, as is also the birefringence. They are non-detrital and belong to the same plane of development as the chlorite and the sericite. They are tentatively referred to sillimanite, although it is not easy to see how such a mineral, characteristic of very high grades of metamorphism, could occur in these rocks which are only

feebly metamorphosed (see later).

A fine-grained grit; S.W. Slope o Rhinog Fach (No.13). Part of "Bluestone Grit" horizon: A fine-grained, muddy grit, bluish-grey in colour at core. Detrital grains are just visible to the naked eye as small (0.3 mm.) grains of quartz set relatively sparsely throughout a muddy matrix. Occasional euhedra of authigenous pyrite occur. The rock is imperfectly cleaved, and surface weathering results in bleaching to a depth varying up to 1/4 inch. Beyond this the colour becomes blue-brown due to weathering out of pyrolusite, and films of that material form along the cleavage planes.

Under the microscope it is very similar to the rock first described under this sub-heading. Small angular and subangular fragments consisting almost entirely of quartz (.06 - .09 mm.) are set in much finer-grained matrix. The quartz grains are of the normal type, and felspar fragments are rare and usually very badly altered. Occasional grains of the detrital colourless garnet are observed (0.06 mm.) and also wispy flakes of white mica. The opaques are frequent, making up 3 - 5 p.c. of the rock volume. They consist of pyrite (cube euhedra; 0.04 mm. - 0.08 mm.) magnetite euhedra, showing square and trapezium outlines (i.e. sections of octahedra), 0.03 - 0.05 mm. Both these are authigenous. Irregular grains and blotchy aggregates of black opaque material are referred to allothigenous magnetite (.01 - .07 mm.).

The matrix of the rock is typical, consisting of a recrystallized intergrowth of quartz and chlorite, with quartz : chlorite, approximately 1 : 1. The amount of chlorite locally increases, frequently giving small areas consisting entirely of chlorite. The chlorite is all of the same type. It is bright green and quite strongly pleochroic, with greatest absorption parallel to the length of the crystal; it has a fairly high refractive index and a low birefringence with blue and purple interference colours. Often good lath-shaped crystals with rectangular terminations and parallel cleavage, and others with "pseudo hexagonal" terminations and no cleavage traces are seen:

The silica is of the clear (chalcedonic ?) type and has an interstitial relationship to the chlorite laths. It has a grain size of approximately 0.01 mm. Scattered throughout are small developments of sericitic material, but it is subordinate. The small reddish hexagon-shaped garnets occur in a similar manner to that already described.

On weathering the chlorite undergoes the changes already described and the connection of these changes with its manganese content is again supported by the separation of pyrolusite on the weathered surfaces.

Mode of Formation of the Grits and their subsequent mineralogical changes.

The materials forming all these grits fall into two classes; the relatively coarse detrital fragments, mainly quartzose, and the very fine-grained uniform matrix material consisting mainly of aluminous and very fine-grained siliceous material. In the coarser grits (I above), the detrital fragments form approximately one-half to two-thirds pf the rock volume, while in the finer grits (II above), the fine-grained matrix material tends to predominate. That the two components were laid down contemporaneously is obvious from their closely intermixed relations. It is also clear that the detrital fragments and the fine-grained matrix belong to two different phases. There was little or no separation of the two phases by the ordinary means of grading under gravity or by lateral transportion. Taking the detrital fragments alone, throughout the thickness of one of the thicker grits there is grading of these: the average side of the contained fragments gets smaller from bottom to top. The finer-ggained deposits, e.g. that from Cil Cychwyn, represents grading of the detrital fragments with increasing distance from their source: they contain a few large fragments and numerous small detrital fragments set in the usual very fine-grained matrix, thus proving the existence of suspended material of very varying sizes. Yet in the coarse grits, the smaller grade of detrital fragments is rare, while the very fine-grained packing material is just as abundant. If both the detrital fragments and the fine-grained matrix represented ordinary suspended material, settling under the laws of gravity, there would at least be present all grades of material from very fine to coarse, in a sediment containing both, and in addition there would be a tendency for the ordinary laws of grading to operate.

Both these conditions tend to be absent. The detrital fragments vary in size according to the laws of grading (with distance of transportation) while the matrix material was invariably present in a constant condition. If then, the fine-grained matrix represents a phase different from the ordinary detrital suspension phases governed by gravity, that phase being finer-grained, must be colloidal suspensate. The grain size of the present matrix material is very small (.01, and since this is a recrystallized state it follows that the original grain size must have been even finer than this, i.e. of colloidal dimensions. It was, therefore, a colloidal suspensate composed of clayey aluminous materials, siliceous materials (probably dilute silica gel) and varying amounts of colloidal manganese carbonate, formed from solution. This suspensate was subjected to constant flocculation and became a constant component of all the rocks of this group from fine grained rock to coarse grits. Since it forms upwards of 50 p.c. of even the coarse grits it follows that accumulation of this material by flocculation must have been taking place very rapidly. Professor Boswell[1] has suggested that co-precipitation of these fine-grained colloidal sediments takes place by the action of electro-positive colloid and that in enclosed or partially enclosed bodies of water, precipitation of fine-grained sediment may take place "at such a rate that even where the supply is not continuous and the depth of water not small the sediment remains undifferentiated into grades." Whether or not such action was induced within these Cambrian sediments, as for example, by the presence of colloidal manganese carbonate (organic matter seems to be entirely absent), flocculation of the fine-grained materials took place continuously and so they became intimately mixed with the coarse detrital material that was periodically laid down within the basin.

Thus in the matrix of these grits, aluminous materials, siliceous material and manganese carbonate were closely intermingled in an extremely finely-divided state. The low-grade of metamorphism, induced by induration at the great depths to which these rocks sank beneath the Caledonian geosyncline, resulted in the recrystallization of this fine-grained matrix. Chlorite and sericite were formed from the aluminous materials, the silica crystallized into its present fine-grained (chalcedonic?)

[1] Boswell, P.G.H. The Action of Colloids in Precipitating Fine-grained Sediments. Geol. Mag. Vol.67. 1930. pp.371-81.

form, and possibly tended to post-date slightly the formation of the chlorite and sericite, spessartite garnet was formed by the combining of manganese carbonate with aluminous materials and silica. All these changes, from the present finely divided and uniform state of the matrix evidently took place "in situ".

In these rocks the small reddish garnet is almost invariably present in uniformly small quantities, while the colourless form varies very considerably from being very abundant to practically absent. This suggests that the reddish garnet tends to pre-date the colourless form, and is a manganiferous almandine. The first manganese to undergo action combines with a small amount of available iron to form the red garnet, and then excess of manganese formed colourless manganese rich spessartite. When only small quantities of manganese were present, the amount of colourless garnet would be small, while the reddish garnet would tend to be constantly developed. Thus the present garnet content of these grits reflect the original manganese carbonate content. Sometimes the manganese was segregated into clots within the matrix (such concentrations are present in the siltstones as white irregular patches). These are now represented by the masses of compact garnetiferous material, which have the appearance of detrital grains.

i. Clayey materials $\longrightarrow$ chlorite and sericite.

ii. Clayey materials (possibly chlorite and sericite) + silica + dialogite $\longrightarrow$ spessartite garnet + CO_2

The Heavy Minerals in the Grits.

Seventeen samples of the gritty horizon immediately above the "bluestone", i.e. 5'6" to 6' above the top of the ore, taken from various localities throughout the area were examined. For brevity this is referred to as the "Bluestone Grit". In addition two samples (Nos.18 and 19 in table) of grits occurring above this horizon, and three samples of Rhinog Grits from different localities were examined. The usual procedure of heavy mineral separation was used: the rock sample was crushed, treated with warm dilute hydrochloric acid, washed, and the separation effected by bromoform (S.G. 2.91). With two samples (Nos. 5 and 22) the treatment with hydrochloric acid was omitted. Confirmatory examination of opaque minerals was also made when necessary by means of an electro magnet.

Throughout the three groups of grits thus examined, the "heavy" minerals were alike in their characteristics. The minerals recorded were; zircon, garnet, tourmaline, anatase, rutile, epidote, enstatite, diopside, biotite, sillimanite, apatité, ilmenite, haematite, magnetite, pyrite, chlotite, and in addition aggregate fragments containing numerous minute colourless garnets. Of these, some of the magnetite, all the pyrite, the chlorite and the garnet aggregates are all authigenous.

Zircon: This mineral occurs in all the heavy mineral residues examined and varies in quantity from 4 p.c. to 65 p.c. of the total allothigenous minerals, a good average figure being 15-20 p.c. Of all the allothigenous minerals, zircon is the most constant in characters and propertions. Three major types were distinguished: colourless, purple and tawny. The colourless variety is by far the most abundant and it occurs in many forms. These can be conveniently divided into three groups: rounded, sub-angular, and euhedral. Although there are considerable variations in size within the same sample and amongst different samples, a general tendency for a decrease in size from euhedral forms, through sub-angular forms to rounded forms is observed. The euhedral forms are water-clear, and show combinations of the tetragonal prism (110) with the tetragonal bipyramid (111), or with the ditetragonal bipyramid(311), or with both. The vary from very stumpy, with length : breadth approximately 1:1 to elongate parallel to the principal axis with length: breadth up to 8:1. They occasionally show incipient zoning around the margins. Occasional crystals free from inclusions are observed, but the reverse is generally the case. Inclusions consist of zircons,

apatites, gas-filled cavities, opaque materials and clouds of indefinable opaque dust. The zircon inclusions are prismatic in form, and often large enough to show perfect bipyramidal terminations. These are often arranged parallel to the length of the host crystal (Fig. No.6), sometimes parallel to the bipyramid faces (No.5), and often are irregularly distributed (Nos.5 and 3). Frequently the inclusions are concentrated in the central region of the crystal. Some of the larger zircon inclusions themselves contain inclusions of a similar nature (No.4). Irregular granules may be zircon; small slender needles are referred to apatite (these are relatively rare); gas- or liquid-filled cavities are not frequent and occur as relatively large irregular globular bodies. Many crystals contain clouds of opaque dust, either more or less uniformly distributed or concentrated in clots or stringers. In size the euhedral forms vary from 0.10 m.m. to 0.20 m.m., averaging 0.12-0.15 mm.

The subangular type are similar to the euhedral forms with the exception of loss of good shape and they are frequently traversed by irregular cracks, due to abrasion. They vary in size from 0.07 mm. to 0.20 mm. averaging 0.10-0.14 mm.

The rounded forms are smaller and often remarkable for the absence of inclusions. They vary from 0.05 mm. to 0.15 mm. and average 0.08 mm.

The tawny forms are somewhat more abundant on the whole than the purple forms. They form from 0 to 10 p.c., with an average of $2\frac{1}{2}$-$3\frac{1}{2}$ p.c. of the allothigenous minerals. They occur in euhedral, subangular and rounded forms. The colour is usually uniformly distributed, though euhedral forms not infrequently show its concentration in zones parallel to the faces of the crystal, as described by A. Brammall[1]. They also contain inclusions: zircon, opaque dust, gas-filled cavities etc. They have similar sizes to the colourless varieties.

The purple zircons vary somewhat in the intensity of the colour, but they are invariably very rounded and almost entirely free from inclusions. They range in size from 0.08 mm. to 0.10 mm.

One green euhedral zircon was recorded from the east side of Diphwys (No.4).

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[1] Proc. Geol. Assoc. Vol.39. (1928). p.28.

Garnet: occurs in all but three of the samples examined, and varies in quantity up to 27 p.c. of the allothigenous minerals. On an average it forms about 5-10 p.c. A division into three groups according to colour is made: colourless, brown and pink. Of these, the colourless variety is by far the most abundant and is almost invariably present, while the brown variety is, on the whole, more frequent than the pink, though both are very sporadic in their occurrence. In shape, the grains tend to be more or less rounded, but they are often irregularly fractured, and, less commonly have six-sided outlies, which have been somewhat modified by rolling. No perfectly euhedral grains occur. The colourless variety shows this tendency to the six-sided habit more frequently than the others. The colourless variety is frequently water clear and free from inclusions, but sometimes they show the following inclusions: opaque matter; opaque dust-like clouds occasionally in abundance; prismatic inclusions referred to zircon; and reddish-brown semi-opaque material referred to haematite. The brown variety frequently contains abundant inclusions, while the pink variety is nearly always free from them. The colourless variety occasionally shows a pitted surface, and is often traversed by irregular cracks, a character also displayed by the brown variety. It is often difficult to distinguish between the pink and the pale brown forms, but the former is usually ~~and~~ freer from inclusions. All types have a similar grain size: 0.05 mm. to 0.12 mm. with an average of 0.08 mm. - 0.10 mm.

Tourmaline is invariably present in all the samples, though there is considerable variation in quantity. It varies from 1.0 p.c. to 10.5 p.b. of the allothigenous minerals, averaging 3-4 p.c. The grains vary from being euhedral to subhedral, irregularly fractured, and, more rarely, quite rounded, in form. The euhedral forms are rhombohedral prismatic crystals with various basal terminations. These may be enumerated as follows: (a) rhombohedral; (b) basal parting; (c) combination of (a) and (b); (d) rare hemimorphic forms showing both (a) and (b); (e) regular parting devoid of definite crystallographic directions; (f) irregularly fractured. The true rounded forms are not common in these samples, but they are of noteworthy occurrence in sample No.13. The brown variety is most common. This frequently grades into an olive-greenish brown and one grain of a pale blue colour was recorded. The brown variety is intensely pleochroic with colour variation from colourless or pale brown to deep brown or very deep brown; also from pale brown to deep greenish brown. The maximum

absorption is obtained when the length of the prismatic crystal is aligned at right angles to the direction of vibration of the lower nicol. Occasional crystals are observed in which end portions are darker in colour than the rest of the crystal. The junction of two such portions of a crystal is abrupt and may be a plane parallel to its rhombohedral termination; this indicates regeneration of the tourmaline in crystallographic continuation with the original crystal. Prismatic crystals frequently show longitudinal striations. Inclusions were frequent: zircons (euhedral and anhedral), cavities (?), opaque particles, clouds of opaque dust, rutile, etc. Often inclusions, especially of the cloudy opaque variety are confined to one end of a prismatic crystal; the distribution of these inclusions is limited on the inner side by planes parallel to the basal terminations of the crystal, a feature which again indicates regrowth of the crystal in crystallographic continuation. It is not possible to date the regeneration of these crystals, but some crystals suggest that it was at least prior to the formation of the grit. The grains vary considerably in size in different samples, but on the whole they vary from 0.05 mm. to 0.20 mm., averaging 0.10 mm.-0.15 mm.

Anatase: This is a fairly characteristic mineral of these rocks, being present in eight out of the twenty-two samples. It was abundant only in one sample (No.11), when it reached 10.8 p.c. of the allothigenous minerals; on an average it formed less than 1 p.c. It occurs chiefly as irregular or tabular grains, sometimes deep blue in colour, but more frequently pale blue and non-pleochroic. The paler grains show high birefringence, but the polarization colours are masked by the original blue colour in the darker grains. Under reflected light they show a pale powder blue colour. They frequently show a distinct cleavage (001), while a tendency for fracture at right angles to this often gives rectangular step-like terminations to the grains. Generally the grains contain dense clouds of black inclusions (ilmenite ?). In some grains the inclusions are so dense that the grains themselves appear to be almost opaque. The inclusions under oil immersion are seen to be granular and devoid of all crystal shape. The inclusions are often concentrated in the central region of the crystal. Only rarely are clear transparent

grains observed. Some grains, the bulk of which contain numerous inclusions, show rectangular developments on the margins quite free from inclusions; these suggest that the inclusion free portions are due to regeneration. The grains are obviously detrital and have suffered a good deal of rolling. In size they vary from 0.08 mm. to 0.40 mm. averaging 0.10 mm. to 0.15 mm.

Rutile.is recorded in half the samples and is never abundant. In two samples it reaches 3 p.c. of the allothigenous minerals, but usually it forms less than 1 p.c. It occurs in small rounded or irregularly fractured grains of a reddish-brown colour. In size they vary from 0.04 mm. to 0.10 mm.

Epidote is one of the most characteristic heavy minerals in these rocks, being recorded in all except two samples. It varies considerably in amount from less than 1 p.c. to 35 p.c. of the allothigenous minerals, while in the Rhinog grits, of three examined, one gave 0.6 p.c. and another 69 p.c. of the total allothigenous minerals. Owing to such wide limits, no good average figure can be given. It occurs in irregular and rounded grains, frequently possessing a good cleavage, with a small (4°-7°) extinction angle. It can be divided into three classes: (a) pale yellowish-green to nearly colourless, transparent, free from inclusions and usually possessing a good cleavage; (b) a deep green variety free from inclusions and usually devoid of cleavage; (c) a "dirty" green variety crowded with cloudy opaque inclusions and often much decomposed. The first named is most abundant. All coloured forms are weakly pleochroic. They usually vary from 0.07 mm. to 0.15 mm., averaging 0.11 mm., but sometimes (e.g. No.12) large platy grains 0.25 - 0.28 mm. occur.

Enstatite is one of the rarer constituents of these residues. In amount it varies up to 5.7 p.c. (No.4), but on an average, when it does occur it forms about 1 p.c. of the allothigenous minerals. It occurs as colourless to dirty yellow or brown, irregular and prismatic grains with faint prismatic cleavages, and parallel extinction. It has a low birefringence, and it is by this property that it is distinguished from epidote. The abundance of epidote in these rocks suggested the presence of zoisite, but in the absence of any grains giving the deep ultra-blue interference colours, it must be regarded as being absent. The enstatite occurs in grains 0.06 to 0.18 mm. in size.

Diopside: This is a very rarely occurring mineral, only five grains in two samples being recorded. They occur as irregularly rounded or fractured prismatic grains with good prismatic cleavage, sometimes fibrous. They are colourless, or very pale greenish-yellow and extinguished at an angle of 25°/30° with the cleavage traces. They vary in size from 0.12 mm. to 0.18 mm.

Biotite.is also a very rare constitutent, two grains only in two samples, being recorded. One was a brown cleavage flake of irregular outline with decomposition to green chlorite around the margins; and the other an irregular grain showing distinct and typical pleochroism with straight extinction. They measured 0.11 mm. and 0.14 mm.

Sillimanite. This only occurred in two of the samples examined, and eight grains were recorded in No.1 and two in No.21. They occur as colourless prismatic grains with irregularly fractured basal terminations, a fairly well marked cleavage, parallel extinction, a positive biaxial interference figure and a high birefringence. They frequently contain inclusions of zircon and spinel (?). They vary in size from 0.07 to 0.12 mm.

Apatite: Owing to the treatment of the rock powders with HCl, this mineral was not recorded as a rule. Three samples were examined without treatment with HCl. In two of these it occurred rarely (six grains altpgether), and in the third it was absent. It can be concluded that it occurs throughout sporadically and in small amount. They occur as small (0.04-0.01 mm.) colourless, rounded or ovoid grains with very low birefringence and straight extinction.

Ilmenite (and Leucoxene). This occurs in practically all samples, but it varies considerably in amount (this may be due to the difficulty in diagnosis, the presence of leucoxene being the chief diagnostic property). It is rarely as abundant as allothigenous magnetite in these rocks. It occurs as irregularly rounded and sub-angular grains varying in size from 0.06 to 0.25 mm., and averaging 0.10 to 0.15 mm. They are coated with the decomposition product, leucoxene, which gives the surface of the grains a white or flesh-coloured appearance in reflected light.

Haematite is not common either as an authigenous or as an allothigenous constitutent. Detrital fragments have the form of irregular reddish-brown opaque masses, 0.05 mm. to 0.12 mm. in size.

Magnetite is by far the most abundant mineral in the heavy residues. The two forms, authigenous and allothigenous, are both present almost invariably, although the relative amounts vary in different samples. Irregularly rounded

and anhedral fragments are distinguished as allothigenous, and the euhedral octahedra and freshly fractured fragments as authigenous. Allothigenous magnetite varies from about 5 p.c. of the whole heavy residue to about 35 p.c. and the authigenous from 0 p.c. to 75 p.c., percentages being, on the average, of a high order. [Owing to the uncertain nature of the method of distinguishing between the two varieties, the division is bound to be arbitrary; it must be noted that this factor affects the percentages of all the other allothigenous minerals, when represented as percentages of themselves.] The euhedra vary in size from 0.05 mm. to 0.35 mm., and the allothigenous forms from 0.05 mm. to 0.20 mm, averaging 0.10 mm. Occasionally the octahedra are covered with a veneer of red haematite, which shows up when the mineral is examined in reflected light.

Pyrite is invariably authigenous. It is almost invariably present, sometimes forming as much as 70 p.c.of the heavy residue. On an average, however, percentages vary from 5 to 20. They occur in good cubes, and in freshly fractured subhedral and anhedral fragments. They usually appear quite opaque but occasionally have a slightly translucent yellowish-grey appearance, with very well developed striations, parallel to the edges. These striations appear as black lines, usually closely packed traversing the crystal face. Some of the crystals possess in addition to the usual cube faces, some of the faces of the pyritohedron (Fig. No.42), and occasionally good cube forms have developed a good octahedral cleavage (No.41). Often the crystals shows a veneer of haematite, soluble with difficulty in HCl, which gives a reddish-brown colour to portions of the brassy crystal in reflected light. The pyrite crystals vary in size from 0.06 mm. to 0.30 mm., averaging 0.10 mm. to 0.20 mm.

A marked tendency is observed for the authigenous magnetite and the pyrite to be present in inverse ratio to one another. That is, when the authigenous magnetite is abundant, pyrite is relatively scarce, and vice versa. This possibly indicates that the original finely divided iron sulphide when recrystallizing after the consolidation of the rock[1], crystallized either as pyrite or was oxidized to form magnetite; or it may indicate that the nature in which the iron was originally laid down, differed

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[1] See ~~Chap~~ section on pyrite, pp 99ff

somewhat locally.

Chlorite is almost always authigenous in character, being one of the products of recrystallization of the aluminous matrix material of the grits. Allothigenous chlorite is probably present in small quantities, but its determination under the circumstances is so difficult that it has not been distinguished.

Garnet Aggregates. These composite fragments are common among the heavy residues from these rocks. They represent small fragments of the matrix of the grits formed during the grinding of the rock. In the separation, they appear as irregular fragmentary grains composed of small globular garnets, often showing distinct hexagonal outlines, intimately mixed with chloritic, sericitic and quartose material. The garnets vary from being quite sparse to being so abundant that they make up practically the whole of the fragment. They vary from colourless and free from inclusions to pale yellow-brown, sometimes clouded by very fine dust-like inclusions. In size they vary from 0.009 mm. to 0.025 mm., averaging 0.015-0.018 mm. The varying abundance of the garnets is due to the varying proportions of the original constituents of the rock matrix. They are regarded as having been formed "in situ", and are mainly spessartite in composition. The matrix of these rocks was originally composed of clayey and siliceous matter, together with manganese carbonate (dialogite). On recrystallization the clayey matter formed chlorite and sericite, while the manganese carbonate combined with both clayey and siliceous materials to form spessartite. Where dialogite was originally abundant, spessartite is now relatively abundant, and vice versa. [Examples of these composite grains are figured in Fig. 6]

General Petrology of the Grits.

The abundance of the angular clear quartz fragments practically all of one type, the relative frequency of "kaolinized" orthoclase, and not infrequent oligoclase indicates the derivation of these grits directly from a nearby ancient, somewhat "acid" gneissic land mass. The general indications as far as the Ardudwy tract is concerned, lead to the conclusion that this land mass lay to the east[1].

The heavy minerals themselves throw little or no light upon the problem of their derivation. Among the transparent heavy minerals, zircons are uniformly the most abundant and regularly distributed, but this is a characteristic of many sediments of all ages. Many are apparently of primary derivation, while there is an abundance of subangular and rounded forms which indicate an origin in sediments. Purple zircons are characteristic and nearly always present; if in small quantity. Dr. W. Mackie[2] regards the Lewisian Gneiss of the North of Scotland as the source of all the purple zircons of Scottish sediments, while Dr. A. Heard[3] and Mr. R. Davies[3] assume that the purple zircons of the Old Red Sandstone of South Wales were directly derived from gneissic rocks similar to the Lewisian Gneiss. The purple zircons of these grits, however, are invariably thoroughly rounded (a condition also noted in the grits of the Bala and Valentian Series in Radnorshire and Carmarthenshire by J.I. Platt[4] and K.A. Davies[4]; by F. Smithson[5] in the Cambrian of Dublin and Wicklow, by S.A. Billinghurst[6] in the Arenig rocks of Caernarvonshire and others) which suggests that they are either not of primary derivation or have travelled very great distances. The former is most likely since the source of these sediments is regarded as having been close at hand (see above).

Among the garnets the colourless variety is most characteristic, a condition also true of the Cambrian rocks of the English Midlands[7] and the

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1 W.G.Fearnsides: Geology of North and Central Wales. Geology in the Field. 1910. p. 792

2 "The Source of the Purple Zircons in the Sedimentary Rocks of Scotland". Trans. Edin. Geol. Soc. Vol.XI. (1923.) p.201.

3 "The Old Red Sandstone of the Cardiff District". Q.J.G.S. Vol.LXXX. (1924.) p.509.

4 "The Conglomerates and Grits of the Bala and Valentian Rocks of the District between Rhayader, Radnorshire [and Llansawel (Carmarthenshire).] Q.J.G.S. Vol.LXXXIX. (1933.) p.213.

5 "Geological Studies in the Dublin District. I. Geol. Mag. Vol.65. (1928.) p.18.

6 "Mineral Analyses of some Ordovician Rocks from Caernarvonshire." Geol. Mag. Vol.66. 1929. p.296.

7 Fleet, W.F.: "The Chief Heavy Detrital Minerals in the Rocks of the English Midlands." Geol. Mag. Vol.62. (1925.) p.102.

Ordovician rocks of Caernarvonshire.[1]

The brown tourmaline, though very characteristic, can scarcely be regarded as a diagnostic mineral.

Epidote varies somewhat in occurrence, but is on the whole very characteristic. It is not a commonly recorded mineral in heavy residues. Platt and Davies[2] record it sporadically in the Bala grits of Mid-Wales, and Smithson[3] records it in a sample of quartzite from Carrickgollogan. It is absent from the Cambrian rocks of the English Midlands. However, it fits in with an origin in a complex similar to that now exposed in the More Complex of Anglesey, where spidote abounds.

The presence of anatase is significant. It is invariably of the blue variety and always has a tabular form, bo bipyramids being recorded (a fact which tends to confirm their allothigenous origin). It is interesting to note that while the blue variety is recorded in the Cambrian rocks of the Midlands, the yellow also is very common[4] while in the Dublin district again the blue variety only is recorded from the Cambrian quartzites[5].

Thus examination of the detrital minerals of the grits leads to the conclusion that the land mass from which they were derived consisted of a complex of granitic gneisses (giving abundant quartz and some felspar), sedimentary rocks, metamorphosed or otherwise (giving the minerals of at least second derivation), metamorphic rocks (giving garnet and possibly epidote)and basic igneous rocks (giving epidote, eustatite and diopside). This would be a complex similar to that which we now have exposed in the Pre Cambrian Complex of Anglesey.

Following ore grit horizon - the "Bluestone Grit" horizon, the grits are coarsest in the south, Barmouth district; in the east, in the neighbourhood of the Cwm Mynach Valley, and in the north, near Moel Ysgyfarnogod and Llyn Dywarchen. They are least coarse in the Artro Valley region, i.e. in the Cwm-yr-Afon workings, Cil Cychwyn workings, and on the western slopes of Rhinog Fach, while they are still fine on the eastern

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[1] Billinghurst, S.A. op. cit. p.295.

[2] loc. cit. p.214.

[3] loc. cit. p.20.

[4] Fleet, W.F. loc. cit. p.98

[5] Smithson, F. loc. cit. p.12.

slopes of Diphwys, though they are somewhat coarser in the intervening region of the west and north-west slopes of Moelfre. This indicates a deepening of the basin towards the present centre of the Harlech Dome, with land tending to lie at least to the east, northeast and southeast. (A discussion of the morphology of the basin of deposition and its surrounding land will be given elsewhere.)

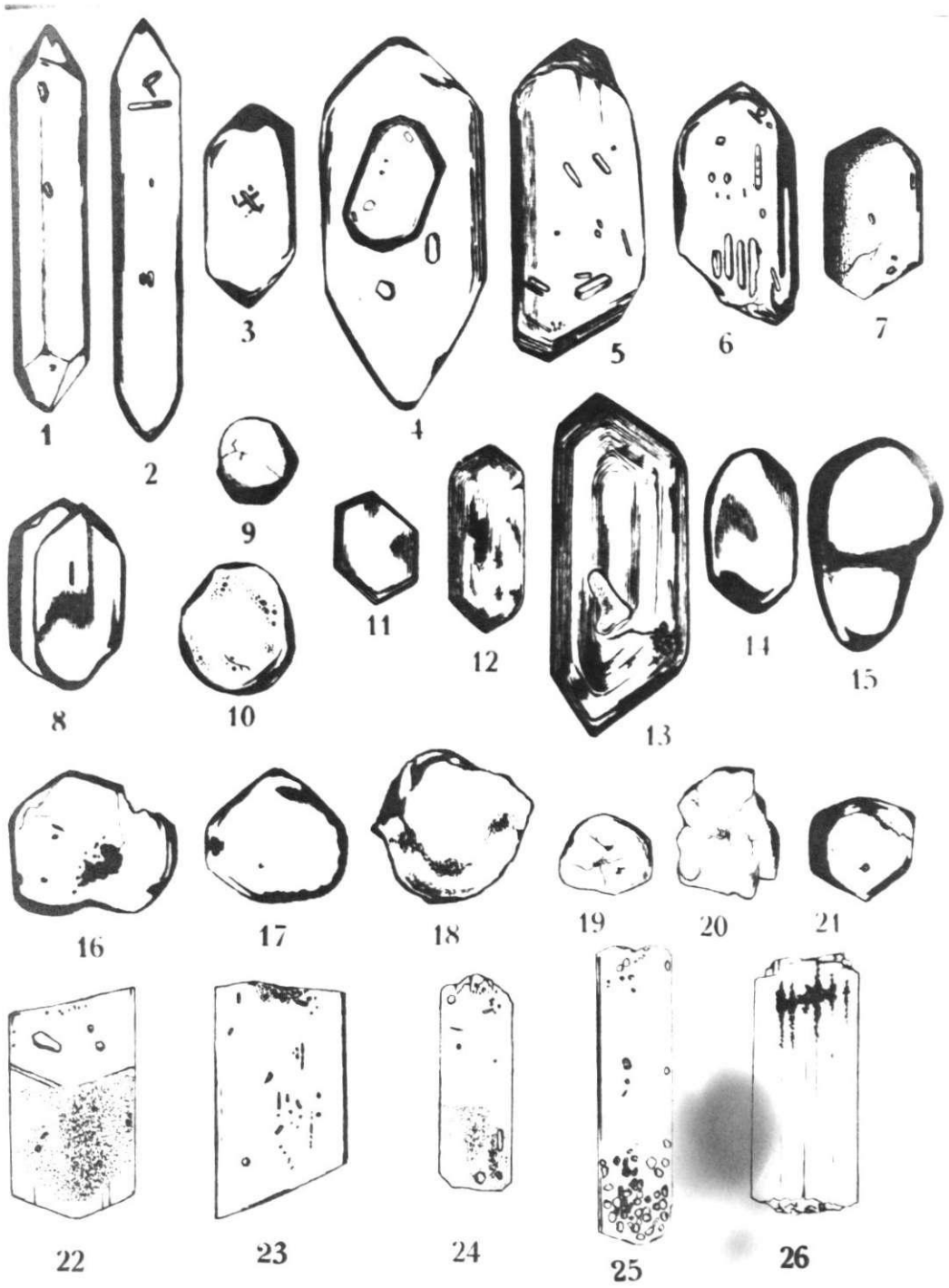

FIG 5.

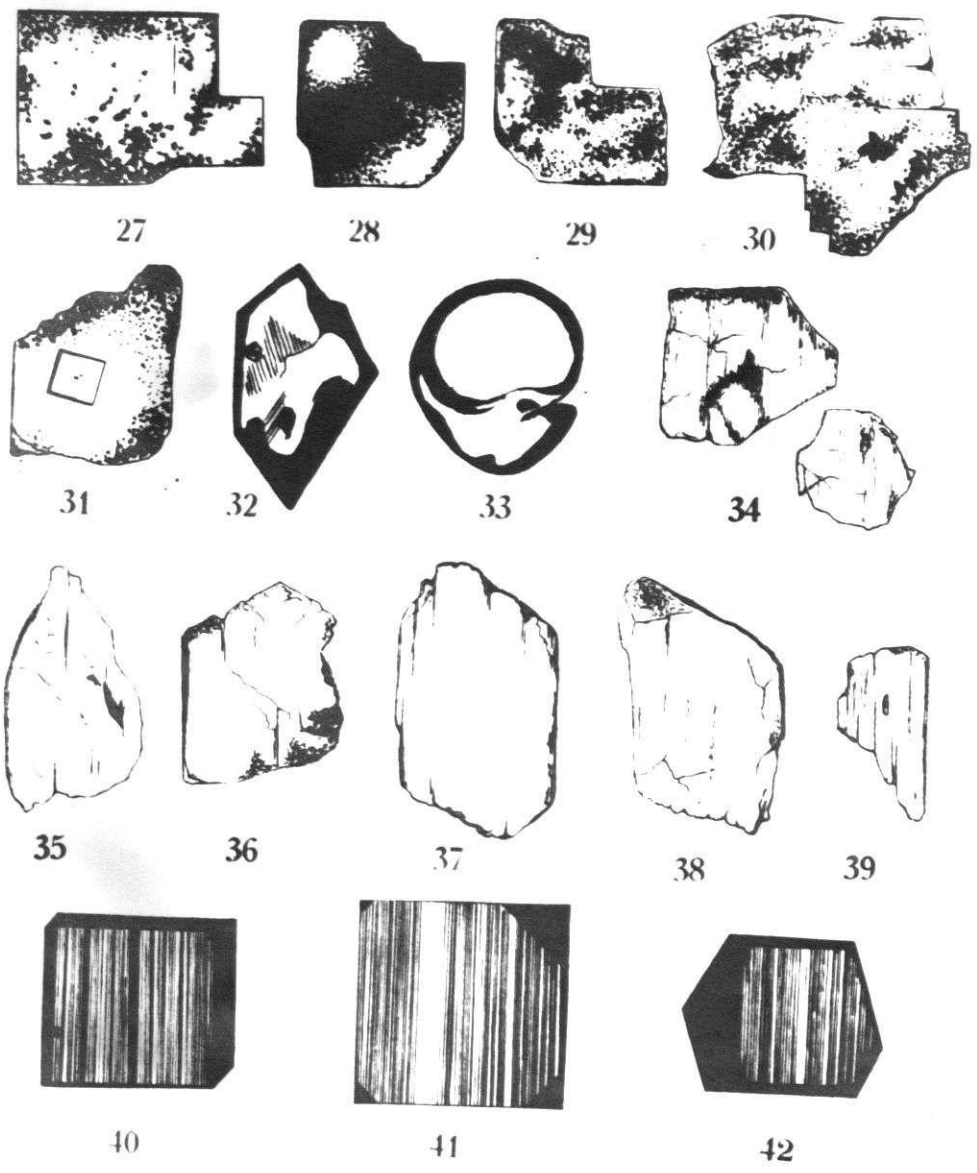

FIG. 5 (contd)

Fig. 5

Zircons.

1. Colourless euhedral form, showing the faces in relief: (No.18.)[1]
2. Colourless, euhedral, elongate form with irregularly orientated inclusions of zircon. (No.7.)
3. Colourless, euhedral form with euhedral inclusions of zircon concentrated in central region (No.18.)
4. Colourless, euhedral form with well shaped inclusions of zircon. One inclusion is very large showing good prismatic form with bipyramidal terminations, itself showing good zoning and containing inclusions of zircon. (No.1.)
5. Colourless, sub-hedral form showing ill-developed marginal zoning, with inclusions of zircon, some orientated parallel to the bipyramid terminations, and some orientated haphazardly; some opaque inclusions also occur. (No.1.)
6. Colourless, subhedral form, with well developed zircon inclusions orientated parallel to the major crystallographic axis of the crystal. (No.19.)
7. Colourless, sunhedral form, with colourless zircon, and opaque cloudy inclusions. (No.1.)
8. Colourless, double form. (No.4.)
9. Colourless, rounded with irregular cracks. (No.1.)
10. Colourless, rounded, form with opaque and minute globular (gaseous ?) inclusions. (No.1.)
11. Tawny, euhedral, stumpy, form showing ill-developed zoning and absence of inclusions. (No.1.)
12. Tawny, euhedral, showing good zoning and clouds of opaque dust-inclusions concentrated in the central region. (No.1.)
13. Tawny, euhedral form. A good prismatic form with (111) and (331) terminations. The zoning is due to the concentration of the colour in layers parallel to the margins of the crystal. Between these zones the crystal more or less approaches a colourless character. The zones are very narrow and numerous, and are more clearly marked when the crystal is aligned parallel to the E-W cross-wire. The

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[1] The numbers in parenthesis refer to the various samples in the accompanying table.

polarization colours are arranged in concentric layers, parallel to the edges of the crystal, i.e. congruent with the zoning. Inclusions: one cavity with irregularly rounded outline, presumably gas-filled; a few small stumpy crystals of zircon; and some clotted opaque material. (No,3.)

14. Purple, rounded form showing tendency to prismatic-bipyramid form (No.2.)

15. Purple rounded form. (No.8.)

Garnets.

16. Colourless, subhedral, showing tendency to hexagonal outline with general rounding. Inclusions of opaque material. (No.7.)

17. Colourless, subhedral, with modified hexagonal outline on one side. (No.2.)

18. Colourless, anhedral, showing pitted surface. (No.8.)

19. Colourless, irregularly rounded with irregular cracks. (No.1.)

20. Colourless, irregularly fractured outline. (No.1.)

21. Brown, showing hexagonal outline. (No.1.)

Tourmaline.

22. Brown, prismatic, showing rhombohedral basal planes at one end. Inclusions of zircon and opaque particles. One end filled with clouds of opaque inclusions limited on inner side by planes parallel to the rhombohedral terminations. (No.1.)

23. Brown, prismatic, with regular terminations devoid of definite crystallographic directions. Inclusions of rutile and zircon. (No.1.)

24. Brown, prismatic; basal terminations by basal parting and irregular fracture. Inclusions of opaque cloudy material truncated on the interior by a plane parallel to basal parting. Also inclusions of zircon. (No.1.)

25. Brown, prismatic; one end crowded with quite large stumpy, six-sided zircons and irregularly shaped crystals of rutile. (No.3.)

26. Brown, prismatic; showing irregularly fractured terminations, longitudinal striations, and clotted opaque inclusions arranged in stringers parallel to the principal axis of the crystal. (No.20.)

Anatase.

27. Pale blue, tabular; showing good outline and opaque inclusions more or less confined to marginal regions. (No.13.)

28. Blue, tabular; showing good form and dense inclusions. (No.11.)

29. Pale blue, tabular; with dense inclusions; one corner broken away along (001) cleavage. (No.11.)

30. Pale blue, irregular, tabular form showing good (001) cleavage and dense inclusions. (No.11.)

31. Pale blue, irregular, tabular grain relatively free from inclusions; bearing euhedral tabular crystal on surface; this latter crystal is not in crystallographic continuation with the major crystal and is quite free from inclusions; it is probably due to regeneration. (No.5.)

Rutile.

32. Irregularly fractured grain of deep amber red colour. (No.1.)

33. Well rounded, foxy-red form. (No,2.)

Epidote

34. Pale yellowish green, irregular grain with fairly good cleavage. (No.1.)

35. Irregularly rounded, pale greenish-yellow grain, with cleavage. (No.4.)

36. Sunangular, pale green; with decomposing margins having abundant inclusions; faint cleavage traces. (No.4.)

37. Almost colourless, water clear grain, subhedral, with faint cleavage. (No.18)

Enstatite.

38. Colourless, prismatic section, with ragged terminations and faint prismatic cleavage traces. (No.4.)

Sillimanite.

39. Colourless, prismatic form, with good cleavage and inclusion of zircon (itself carrying an inclusion of rutile), orientated parallel to prism faces. (No.1.)

Pyrite.

40. Euhedral; showing well developed striations. (No.18.)

41. Euhedral; showing well developed striations, and good (111) cleavage. (No.14.)

42. Euhedral; with good striations and pyritohedron faces. (No.19.)

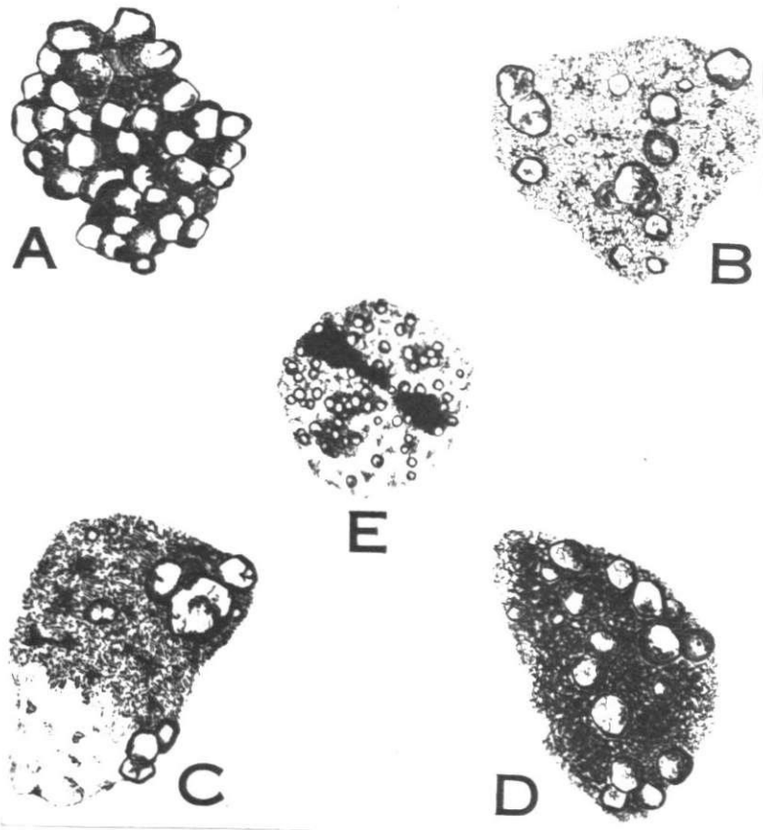

Fig. 6. Garnet Aggregates.

A. Mass composed practically entirely of garnets, with dark indefinable material scattered between the grains.

B. Colourless garnets scattered sporadically through a very fine-grained matrix of pale green chlorite.

C. Small colourless garnets in chloritic and siliceous matrix.

D. Colourless garnets in cloudy, chloritic matrix.

E. Minute colourless garnets set in silica-chlorite matrix. Magnification x 300 diams.

No	Rock	Locality	Allothigenous minerals. Zircon colourless (rounded)	Zircon colourless (sub-angular)	Zircon colourless (euhedral)	Zircon purple	Zircon tawny	Total zircon	Garnet colourless	Garnet pink	Garnet brown	Total garnet	Tourmaline	Anatase	Rutile	Epidote	Enstatite	Diopside	Biotite	Sillimanite	Apatite	Ilmenite	Haematite	Magnetite	Authigenous minerals. Magnetite	Pyrite	Chlorite	Aggregates of minute garnets	Allothigenous minerals as % of the heavy residue
1	Bluestone Grit	St. John's Church, Barmouth		2·8		0·1		2·9	1·9		0·1	2·0	0·6		0·1	0·6	0·1			0·2	NA	3·0	0·2	5·6	77·7	2·6	3·4	1·0	15·3
				18·6		0·5		19·1	12·3		0·9	13·2	3·7		0·5	4·2	0·6			1·4	ND	19·5	1·4	36·4					
2	do	do.	0·8	3·5	2·2	0·1	0·2	6·8	6·4			6·4	2·9		0·4						ND	2·0	1·8	6·8	47·4	5·3	15·8	4·4	27·1
			2·8	12·9	8·3	0·4	0·9	25·3	23·5			23·5	10·5		1·4						ND.	7·4	6·9	25·0					
3	do.	Hafotty Mines.	0·7	2·7	1·5	0·2	0·7	5·8	0·5		1·5	2·0	0·2		0·7	1·0					ND	6·8	1·0	6·7	60·5	3·9	1·9	9·5	24·2
			3·0	10·9	6·0	1·0	3·0	23·9	2·0		6·0	8·0	1·0		3·0	4·0					NA	28·0	4·0	28·1					
4	do.	East side of Diphwys.		2·3		2·8		31·1					5·8			26·8	4·3	0·6			ND	2·5		4·2	1·0	21·5	1·9	0·3	75·3
				37·6		3·7		41·3					7·7			35·6	5·7	0·8			NA	3·3		5·6					
5	do.	[Each] W. side of Mynydd Cwmtmyn-	1·9	6·7	2·4	0·8	1·1	12·9	1·9	0·8	1·1	3·7	1·3	0·6							0·7	2·8		20·9	4·1	48·8	4·1		43·0
			4·4	15·7	5·7	1·7	2·6	30·1	4·3	1·7	2·6	8·6	3·1	1·3							1·7	6·5		48·7					
6	do.	E. side of Cwm Mynach Valley	0·4	1·0	0·4	0·5	0·1	2·4	0·8	0·8	0·3	1·9	0·3			3·1					ND	0·6		5·2		61·5	13·9	11·1	13·5
			2·9	7·7	2·9	3·8	0·9	18·2	5·8	5·8	1·9	13·5	1·9			23·0					ND	4·8		38·4					
7	do.	N. end of Moelfre Mines	1·4	1·7	2·2	0·1	0·6	6·0	4·0			4·0	1·1			0·2					NA	5·9		12·0	60·1	4·6	6·1		29·2
			5·0	5·8	7·4	0·4	2·1	20·7	13·6			13·6	3·7			0·8					ND	26·2		41·1					
8	do.	Hendre Mines	1·7	3·5	2·4	0·7	1·4	9·7	4·5		1·0	5·5	1·1		0·7	0·7					NA	12·2		25·0	17·0	9·4	16·0	0·3	57·3
			3·0	6·1	4·2	1·2	2·4	16·9	7·9		1·8	9·8	1·8		1·2	1·2					ND	21·2		43·7					
9	do.	Coed Mines: Artro Valley	1·5	1·5	1·2	1·3		5·5	13·5	0·3	~~1·3~~	13·8	1·8		0·5	0·7			0·3		ND		5·5	23·3	37·8	3·5	6·3	1·0	51·4
			2·9	2·9	2·4	2·5		10·7	26·4	0·5		26·9	3·4		1·0	1·5			0·5		ND		10·7	45·3					
10	do.	Above Coed Dol-y-Bebin.	5·5	7·4	2·2	1·4	3·0	19·5	0·5		1·1	1·6			0·3	0·3			0·3		NA	3·8	0·6	3·8			69·8		30·2
			18·2	24·6	7·3	4·6	10·0	64·7	1·8		3·6	5·4			0·9	0·9			0·9		ND	12·7	1·8	12·7					
11	do.	Nr. Fishpond, Coed Lleity-Walter	2·9	3·4	2·9	0·2	1·3	10·7	4·3	2·0	0·5	6·8	1·8	6·8	0·2	0·7					NA	3·5		28·2	9·4	3·6	21·7	1·6	63·7
			4·5	5·4	4·5	0·3	2·0	16·7	6·8	3·1	0·9	10·8	2·8	10·8	0·3	1·1					ND	13·3		44·2					
12	do.	Cil Cychwyn	0·1	0·2		0·1		0·4	1·0		1·2	2·2	0·9			0·5					NA	2·2		9·9	30·5	43·0	9·8	0·6	16·1
			0·7	1·3		0·7		2·7	5·9		7·3	13·2	5·3			3·3					ND	13·9		61·6					
13	do.	S.W. Slopes of Rhinog Fach	0·1	0·6	0·1		0·1	0·9	2·1		0·3	2·4	1·3	0·4		0·1					NA	1·8		37·3	37·3	18·6			44·1
			0·3	1·4	0·1		0·1	1·9	4·9		0·7	5·6	3·0	0·8		0·1					ND	4·0		84·6					
14	do.	Cwm-yr-Afon Mines	0·2	0·8	0·1			1·1	0·4	0·1		0·5	0·3	0·1	0·2	0·2					NA	1·0		5·1		71·1	20·4		8·5
			1·5	9·8	1·5			12·8	5·3	0·7		6·0	3·1	0·7	3·1	2·3					ND	11·4		60·6					
15	do	Llyn Eiddevy Mawr.	0·4	1·3	0·2		0·1	2·0	2·8		0·1	2·9	2·3	0·2		0·2					NA	1·6		35·1	15·1	3·0	37·5	0·1	
			0·8	2·9	0·5		0·2	4·4	6·3		0·2	6·5	5·2	0·5		0·4					NA	3·6		79·4					
16	do	S.W. side of Moel-ysgyfarnogod.	1·1	0·8	0·5	0·2	0·3	2·9	0·6	0·1	0·5	1·2	0·5	0·2		6·4	0·5				NA	2·6		5·4	64·9	6·3	9·1		19·7
			5·5	4·2	2·5	1·2	1·2	14·6	3·0	0·6	2·4	6·0	2·5	1·2		32·7	2·4				N.D	13·3		27·3					
17	do	E. side of Llyn Dywarchen	1·4	2·9	1·3	0·9	0·9	7·4	1·9		1·4	3·3	0·5		0·4	2·2	1·3				NA	1·4	2·2	13·1	53·0	6·7	8·5		31·8
			4·2	9·0	4·3	2·8	2·8	23·1	5·9		4·3	10·2	1·4		1·4	7·1	4·3				N.D.	4·3	7·1	41·1					
18	Grit	8½′ above ore; Barmouth	1·3	3·9	5·2	0·1	0·2	10·7	2·4		0·1	2·5	1·0			9·6	0·5	0·3			NA	0·8	1·1	6·1	36·7	17·0	13·4	0·3	32·6
			4·0	11·8	15·9	0·3	0·7	32·7	7·2		0·3	7·5	3·1			29·4	1·7	1·0			ND	2·4	3·4	18·8					
19	do.	14½′ above ore; Barmouth	6·9	6·6	5·3	0·3	1·7	20·8	0·3		0·3	0·6	0·7			1·9					NA	1·9	0·6	6·0	38·1	18·3	11·1		32·5
			21·4	20·5	16·3	0·9	5·1	64·2	0·9		0·9	1·8	1·7			6·0					ND	6·0	1·7	18·6					
20	Rhinog Grit	S.W. Slopes of Moelfre	2·1	6·2	3·0	0·5	0·2	12·0	0·5		0·2	0·7	1·0	0·2	0·3	2·7	0·5				NA	10·7		9·7		26·7	16·3	0·2	56·8
			3·8	10·9	5·3	0·9	0·3	21·2	0·9		0·3	1·2	1·8	0·3	0·6	38·1	0·9				ND	18·8		17·1					
21	do.	N. Slopes of Moelfre	1·4	2·6	1·1	0·6	0·3	6·0					3·1		0·3	49·6	0·9			0·3	NA	6·9		4·6	9·1	18·3	0·9		71·7
			2·0	3·6	1·6	0·8	0·4	8·4					4·4		0·4	69·2	1·2			0·4	ND	9·6		6·4					
22	do.	SE Slopes of Rhinog Fawr.	0·8	1·1	0·7	0·2	0·5	3·3			0·5	0·5	0·2	0·3		0·2	0·5				0·3	27·0		8·5	5·0	29·7	24·3	0·2	40·8
			1·9	2·6	1·7	0·5	1·1	7·8			1·3	1·3	0·6	0·8		0·6	1·1				0·8	66·2		20·9					

Table showing the quantitative distribution of the Heavy Minerals in the grits. The numbers correspond with those of pp 52-3.
The black figures show the various species as percentages of the total Heavy Residue.
The red figures the percentages of the allothigenous minerals present.

The grits examined with special reference to their heavy mineral content are represented in the table. They are as follows:

1. Grit above ore[1], St. John's Church Barmouth. Taken from base of the grit band. A coarse blue-grey grit with abundant colourless and dark siliceous quartz grains, angular and subangular and up to 3 mm. (averaging 1-2 mm.). Weathering to deep blue-black colour indicating abundant manganese.

2. Same as (1), taken slightly above base. Fairly coarse blue-grey grit, similar to (1), though not quite as coarse.

3. Grit above ore; Hafotty Mines, 2 miles N. of Barmouth. A coarse, massive, grey grit; grain size 1-2 mm., angular and subangular quartz grains predominant.

4. Grit above ore; E. side of Diphwys: somewhat fine-grained blue-grey grit, with matrix material abundant; grain size averaging 1 mm.

5. Grit above ore, W. side of Mynydd Cwm Mynach. A very coarse, massive, light blue-grey grit; clear, angular and subangular quartz fragments very abundant, varying from 1 to 4 mm. Matrix material not abundant and consequently manganese content not high, weathered surfaces covered with brown-black veneer, containing manganese dioxide.

6. Grit above ore; E. side of Cwm Mynach Valley. A coarse, massive, blue-grey grit with abundant angular and subangular quartz fragments 1-2 mm.

7. Grit above ore; N. end of Moelfre Mines. A coarse, cleaved, grit; grey when fresh, stained blue-black when weathered; grain size 1-2 mm., with quartz fragments predominating.

8. Grit above ore; Hendre Mines, Moelfre. A fairly coarse, blue-grey grit with angular and subangular quartz grains up to 2 mm.; weathers readily, showing a considerable manganese content.

9. But above ore; Coed Mines, Artro Valley. A fairly coarse, blue-grey grit with abundant and colourless quartz grains up to 2 mm. Slightly cleaved.

10. Grit above ore; above Coed Dol-y-Bebin. A coarse massive grit, blue-grey in colour and consisting essentially of quartz fragments up to 2 mm., and of angular and subangular outline. Matrix content low.

11. Grit above ore; Nr. Fishpond, Coed Lletty Walter. A fairly coarse, blue-grey, cleaved grit; average grain size 1.5 mm.; similar to

[1] Err. For "Grit above ore" in all samples read "Bluestone Grit".

No.9; weathers blue-black.

12. Grit above ore, Cil Cychwyn Mines, Nantcol. A fine-grained, dark blue-grey grit similar to No.13.

13. Grit above ore; Rhinog Fach. A very fine-grained grit (gritty-mudstone) of blue-grey colour, weathering brownish-black due to presence of manganese; abundant small grains of quartz, visible microscopically up to 0.3 mm.

14. Grit above ore; Cwm-yr-Afon. A fairly coarse, blue-grey grit with quartz grains 1-3 mm. (averaging 1-5 mm.). Manganiferous weathering abundant; Pyrite crystals occur scattered throughout up to 2 mm.

15. Grit above ore; Llyn Eiddew Mawr: fine grained grit with a coarse layer ($\frac{1}{8}$ to $\frac{1}{2}$ inch thick) at base. Upper portion similar to (12). Lower gritty portion consisting of angular and subangular quartz fragments up to 1 mm. Manganiferous weathering well marked.

16. Grit above ore: S.W. side of Moel Ysgyfarnogod. Coarse, massive, compact, blue-grey grit with angular and subangular quartz fragments up to 4 mm., and averaging 1.5 to 2 mm. Frequent small cubes of pyrite scattered throughout (similar to 14.)

17. Grit above ore; E. of Llyn Dywarchen. A coarse blue-grey grit, hard and massive, with abundant quartz grains up to 1.5 mm. Blue-black decomposition products indicate presence of considerable manganese.

18. Grit $8\frac{1}{2}$' above ore; St. John's Church, Barmouth. Coarse, massive, blue-grey grit of grain size 1-2 mm. Manganiferous weathering.

19. Grit $14\frac{1}{2}$' above ore; St John's Church, Barmouth. A very coarse, massive blue-grey grit, with very abundant angular quartz grains, averaging 2-$2\frac{1}{2}$ mm.; weathering bluish black and indicating fairly considerable manganese content in matrix.

20. Rhinog Grit; S.W. slope of Moelfre. A very coarse green-grey grit similar to 21.

21. Rhinog Grit; N. end of Moelfre. A coarse green-grey grit with abundant quartz and felspar grains of average size 1-3 mm.; weathered rusty red.

22. Rhinog Grit; S.E. slope of Rhinog Fawr. A hard compact blue-grey grit with abundant angular quartz grains 1-2 mm.

THE MANGANESE-BEARING MUDSTONES.

The Normal Mudstones.

1. Petrography.

The mudstones to which greatest importance was attached were those immediately associated with the main manganese-bearing rocks. These belonged chiefly to the "bluestone" horizon, which comprises 5 ft. 6 inches to 6 ft. of striped mudstones immediately succeeding the ore band. Apart from the variations which occur in the mudstone-matrix of the pyrite bsnd below the ore, and which are described elsewhere, the normal mudstones are similar in character throughout the area. Minor differences, among which are the variations of the dialogite content from "bluestone" to other mudstones, and the presence or absence of minute euhedra of tourmaline, serve to differentiate minor types among the mudstones.

Many mudstones were examined: the characteristics of a typical "bluestone" will be described in detail; a shorter description of the minor differences shown in others will be added.

For the purposes of description distinction is made between the tourmaline-free mudstones and the tourmaline-bearing mudstones, although as far as the mudstones themselves are concerned this distinction does not seem to be of vital importance.

Tourmaline-free mudstones.

A mudstone from the "bluestone" horizon, 2 ft. 6 inches above the top of the ore band, at St. John's Church, Barmouth, has the following characteristics:

Macroscopic characters. A fine-grained blue-grey mudstone; is well bedded with a very regular thinly striped bedding, the individual laminae varying on an average from 0.5 mm. to 1.0 mm. and sometimes 1.5 mm. There is no fissility along the junctions of these layers and the whole forms a compact mudstone. The lamination consists of an alternation of darker and lighter blue-grey materials. The bedding is remarkably regular, the junction between succeeding laminae being parallel plane surfaces. Very rarely a thicker band up to 1½ inch or more of the

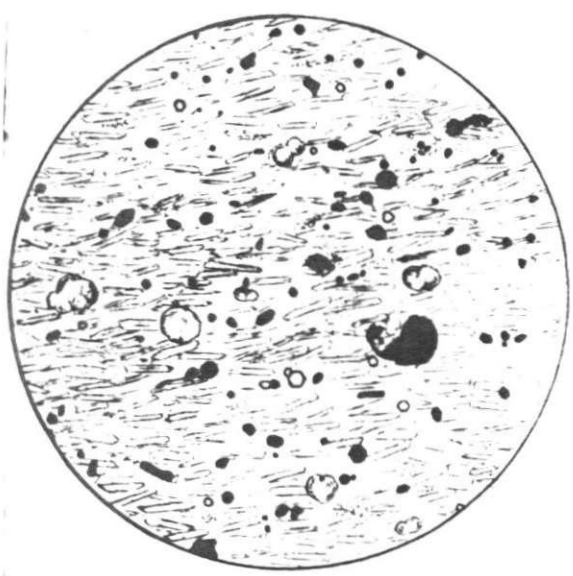

Fig. 7 Normal "Bluestone"; St. John's Church, Barmouth.

The normal mudstone of the darker blue-grey bands concists of colourless and reddish-brown garnets, globules of dialogite, and magnetite, set in a matrix of intergrown quartz, chlorite and sericite. The laths of chlorite and sericite tend to be orientated in one plane. Magnification x 375 diams.

darker material occurs, but the regular thinly bedded character is the rule. No individual minerals can be recognized, even with a lens, with the exception of an occasional small crystal of pyrite.

Microscopic characters.

(a) The darker bands: Consist of a very fine-grained intergrowth of detrital quartz fragments, lath-shaped crystals of chlorite and sericite, and not abundant colourless and reddish brown garnets, allothigenous and authigenous magnetite, and dialogite.

The quartz is of the normal clear, colourless variety, with some minute inclusions. In ordinary light it forms the colourless, low refractive, background in which the other minerals appear to be set. Under crossed nicols, itt presents a mosaic-like appearance, and owing to the recrystallization of the interstitial argillaceous material, the grains possess no well defined margins. The fragments vary in size from 0.005 mm. to 0.015 mm. with an approximate average of 0.010 mm.

The chlorite and sericite occur in intergrown lath-shaped crystals, varying from 0.015 mm. to 0.30 mm. long and from 0.002 mm. to 0.007 mm. wide. The chlorite is the green pleochroic variety similar to that described in the other sediments. The sericite is almost colourless, but is best distinguished by its higher birefringence. The laths of the two minerals are closely intergrown, and are orientated in a definite plane, which appears to be slightly inclined (15° - 18°) to the direction of the bedding of the rock (see fig. 7). In hand specimen the rock is not well cleaved, but has an eneven fracture; this alignment of the chlorite and the sericite laths may have resulted from the directional forces, which, had they been stronger would have produced well marked cleavage. These two aluminous minerals are approximately equal in amount to the quartz.

The colourless garnets have characters similar to those in the matrix of the grits, and are not abundant. They occur in euhedral six-sided crystals with an average size of 0.005 mm. to 0.012 mm. The reddish brown garnet is slightly more abundant than the colourless variety. It varies in size from 0.005 mm. to 0.022 mm.

The magnetite is partly allothigenous (small irregularly shaped grains) and partly authigenous (euhedral, with four-sided outlines in section). It varies in size up to 0.040 mm.

The carbonate (dialogite) varies considerably in amount from layer to layer, and is the most variable constituent of the rock. It occurs as small equidimensional globular masses, 0.015 mm. to 0.020 mm., which exhibit no characters that suggest either a radial or a concentric structure. The refractive index has a large range, the upper limit being high and the globules often stand out as clearly as the garnets, from which they are distinguished by their larger size, anhedralism and birefringence. The birefringence is high, giving very bright polarization colours of a high order.

(b) The paler bands: The palest of these bands consist very largely of the small globular granules of dialogite, with only subordinate amounts of quartz, chlorite and sericite. Both types of garnet occur, the colourless form is more difficult to recognize on account of the greater quantities of dialogite of similar colour and refractive index which are present. The garnets are not abundant and compared with the darker bands there is a marked decrease in the amount of the reddish variety.

Less pale bands contain less grahular carbonate material ad more chlorite-sericite-quartz material, but, apart from this variation in the proportion of the constituents, the characteristics are the same.

The colour differences in the bands are thus reflected mineralogically by variations in the amount of admixed dialogite, the ratio of quartz to chlorite and sericite remaining approximately constant throughout. In the darker bands, the coloured chlorite-sericite-quartz material predominates, while in the paler bands, the colourless dialogite is much more abundant. Bands occur representing all stages of transition from the darkest bands to the lightest bands.

Although the various laminae are clearly differentiated in hand specimen, under the microscope the junctions are not at all clearly marked. The transition from one band to another, usually fairly rapid, is most obvious when viewed between crossed nicols. In the same locality and

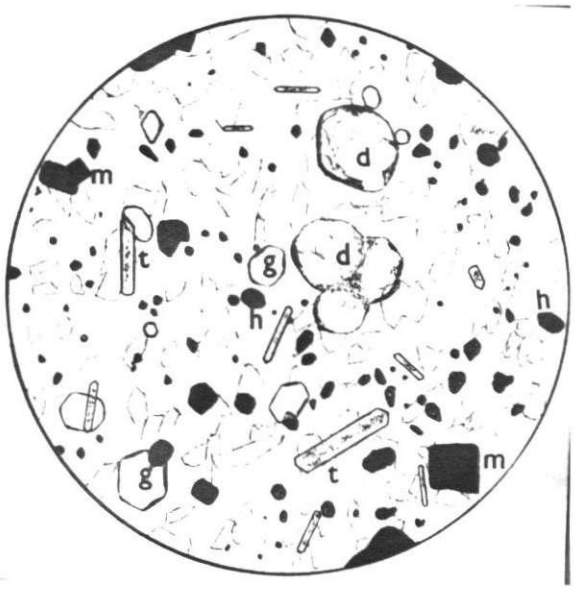

Fig. 8 Mudstone matrix of pyritiferous band in lower "Bluestone" East side of Diphwys.

Showing authigenous tourmaline, spessartite, reddish-brown garnet and magnetite in a ground mass of quartz and chlorite.

t: tourmaline; g: spessartite; h: reddish-brown garnets; d: dialogite globules; m: magnetite.

Magnification x 375 diams.

about 24 ft. above the top of the manganese ore band, a blue-grey mudstone consisting of regularly thinly bedded layers was similar to the above with the exception that the layers differed only slightly in colour, all tending towards a general dark blue-grey colour. The banding of the rock is best exhibited on the weathered surface, the intensity of the pyrolusite weathering showing up this banding very well.

Microscopically the characters of this rock are the same as those described above, i.e. it consists of an admixture of quartz, chlorite and sericite with anhedral colourless and reddish-brown garnets, some magnetite, and some globular granules of dialogite. The laths of intergrown chlorite and sericite tend to be more stumpy and there is a general tendency for orientation in one plane, which is again at 15° - 18° to the bedding. Again the only differences between the darker and the lighter bands is in the proportion of dialogite present.

Tourmaline-bearing mudstones.

"Bluestone" with pyrite crystals, from the eastern slopes of Diphwys. The development and general relationships of the pyrites in these rocks is considered elsewhere (see p.108).

Microscopically, the mudstone consists of a very fine-grained admixture of fragmental quartz, chlorite, sericite, dialogite, magnetite, spessartite and tourmaline (see fig. 8). The quartzose material is the most abundant and makes up approximately 70 - 80 p.c. of the rock. The grains have angular and subangular outlines, giving a mosaic pattern between crossed nicols, and vary in size from 0.008 mm. to 0.014 mm. The green chlorite is scattered uniformly throughout, in small indefinable masses or minute lath-shaped crystals about 0.015 mm. to 0.025 mm. long with "pseudo-hexagonal" terminations. It occasionally occurs as a coating to authigenous magnetite crystals, and possibly has a similar relationship to these as the chlorite-silica zones have to the pyrite crystals. The chlorite forms 5- 10 p.c. of the rock.

The carbonate material is not very abundant and is best defined under crossed nicols. It occurs in scattered globular granules and forms about 1 - 2 p.c. of the rock.

The spessartite garnets are scattered uniformly throughout.

They have good outlines and are small (0.007 mm. - 0.015 mm.). They form 2 - 3 p.c. Also associated with them are the small reddish-brown garnets.

Evenly distributed and not of uncommon occurrence in this section are minute lath-shaped euhedra of tourmaline. They occur in good prismatic crystals with perfectly developed rhombohedral and basal parting terminations, rare crystals being hemimorphic. They are pleochroic with greatest absorption at right angles to the length of the crystal, i.e. X < Z with

X - pale yellowish green Z - greenish brown.

The crystals possess minute inclusions of transparent and opaque material, which are too small to be recognizable. In size the tourmaline crystals vary from 0.020 mm. to 0.035 mm. long and from 0.005 mm. to 0.015 mm. wide, with the length : breadth ratio about 10 : 1 to 4 : 1. On account of their euhedralism, their approximate equal size and their uniformity in specie, they are regarded as being authigenous in origin. They form only a very small proportion of the rock. (see fig. 6).

Black opaque minerals occur abundantly. Euhedral cubic magnetite 0.02 mm. - 0.035 mm. makes up 2 - 5 p.c. and is authigenous. Smaller black opaque fragments (0.005 mm.) have an irregular shape and are detrital.

Scattered throughout this rock matrix occur small bodies, spheroidal in shape, having an oval outline in sections cut at right angles to the bedding. The long axes of these bodies are aligned parallel to the bedding; that is, the spheroids were formed by the compression of small spherical bodies parallel to the bedding. They vary from 0.3 mm. to 2 mm. in horizontal diameter, and have a long diameter: short diameter ratio of 4 : 1 to 3 : 2. (see fig. 21). They are, in hand specimen, very clearly and abruptly marked off from the rock matrix. Under high power, they are seen to consist of a very fine-grained intergrowth of dialogite and spessartite, similar to that of the ore. Even under oil immersion objective, the passage from spheroid to rock matrix is seen to be quite abrupt, suggesting that the material forming these bodies must

have been immiscible with the fine grained rock material and no diffusion of the adjacent materials took place. In some of the spheroids the proportion of spessartite to dialogite gets less towards the centre of the body, and this is accompanied by a dimunition of purplish tinge which characterizes them. It thus appears that the faint purplish colouration is due to the spessartite.

A normal "bluestone" from the locality of the Egryn Mines (see Pl4. fig.3) was very similar in appearance to the rock from Barmouth already described. The alternations are of slight variations of the paler type of material, and in bulk the rock is lighter in colour than the Barmouth "bluestone". (This would appear to indicate a greater general dialogite content). With a lens, small "points" of a black mineral are seen in fair abundance. This mineral is magnetite and the small crystals can be readily isolated from the rock powder by means of an electro-magnet.

The minerals present are identical with these of the normal "bluestone" with, in addition, rare minute crystals of tourmaline as described above. Larger quantities of authigenous magnetite have been developed. These euhedral magnetite crystals are 0.020 mm. to 0.040 mm. in size and occur throughout but are relatively more abundant in the darker bands, where the normal detrital material is also more abundant, than in the paler bands. The crystals often tend to be surrounded by narrow zones of green chlorite. There is again a tendency for the chlorite-sericite laths to be in the same plane, about 30° with the bedding. (An ill-developed cleavage is approximately at 45° with the bedding).

A "bluestone" mudstone from the Hafotty region, 2 miles north of Barmouth, consists of fine-grained blue-grey mudstone, not very dark in colour, which differs from the typical "bluestone" in that the regular thinly bedded laminae are not well developed and in that they contain many intercalated bands of white or cream coloured carbonate material and an occasional band of flinty, pinkish-cream "ore" material. These layers are gently flexured and not persistent. They sometimes peter out gradually, end abruptly, or may possess lenticular swelling and thinning. Sometimes they occur merely as isolated elongated lenticles. In thickness these irregular bands vary from $^{1}/_{16}$th inch to $^{1}/_{2}$ inch with an

average in the more persistent bands of about 1/12th inch. These bands consist essentially of dialogite and weather readily to pyrolusite. The mudstone itself can be seen with a lens to contain abundant magnetite crystals which appear as minute faceted crystals which reflect light.

Microscopically the mudstone material is quite normal consisting of a fine-grained admixture of quartz, chlorite, sericite, subordinate colourless and reddish garnets, globules of dialogite, authigenous magnetite and rare authigenous tourmaline. The cream and white bands are composed almost entirely of a massive aggregate of globular granules of dialogite. Colourless garnets occur, but they are not easy to distinguish, and the brown garnets are almost absent from the more massive bands. The junctions of these carbonate bands with the mudstone are clearly marked and can be delineated even under the higher powers of the microscope.

A mudstone occurring between the pyrite band and the ore in the south-west slopes of Rhinog Fach also contained tourmaline: A dark blue massive mudstone, with occasional narrow bands, 1 - 2 mm. thick, of paler material. Abundant magnetite is recognizable with the aid of a lens and occasional thin layers of pyrite crystals 0.1 mm. to 0.6 mm. It consists of an intimate mixture of detrital quartz fragments 0.005 mm. to 0.015 mm., lath-shaped chlorite and sericite (the latter subordinate), and dialogite. The dialogite is abundant (up to 50 p.c.) but the globular granule habit is not so evident as in the typical "bluestone". The chlorite laths are orientated quite haphazardly. The garnets are much more rare than in the normal "bluestone", and the reddish-brown variety is again relatively more abundant than the colourless variety. Rare scattered grains of authigenous tourmaline occur. The magnetite crystals are scattered more or less uniformly throughout. They are minute octahedra, varying in size from 0.025 mm. to 0.045 mm. They are very abundant and make up 20 - 25 p.c. of the rock. They are obviously authigenous.

Mudstone with Spherulitic developments.

A mudstone from the "bluestone" horizon in the Hafotty region had the following characters:

It consists of a not well "striped" blue-grey mudstone and contains irregular developments of white, cream and pinkish-cream bands. These have the same irregular characters as above described. In addition a few narrow bands of pale purplish-white "ore" material occur. These are 1/16th - 1/12th inch in thickness and have an irregular lateral behaviour, though they tend to an approximate uniform thickness. Sometimes the band gives way laterally to a series of spheroidal bodies developed along the same horizon. Magnetite can again be observed in the mudstone with the aid of a lens.

Microscopically the mudstone is approximately normal in character. There is a tendency to increased development of reddish-brown garnet, and the crystals have a slightly larger average size (0.020 mm. to 0.025 mm.). This increase appears to be unaccompanied by a corresponding increase in the amount of colourless garnet, but there seems to be a marked decrease in the amount of pale green chlorite. The increase in reddish-garnet and the decrease in chlorite may be reciprocal. Rare small crystals of authigenous tourmaline occur. The amount of carbonate varies considerably in different layers, but it nearly always occurs in the form of globular granules.

The white and cream bands of irregular form consist partly of the massive aggregation of globular granules of dialogite noted in the last slide. There are, however, significant modifications of this type. Frequently spherulites are developed of a similar nature to those in the sphaerodialogite band (pp117-130). These are often particularly well developed, varying from 0.060 mm. to 0.14 mm. in diameter, and with well developed central areas of darker colour and exhibiting excellent black crosses between crossed nicols. The spherulites are best developed when they are not packed closely together into a massive mosaic, and occur usually near the margin of the band. The interstitial areas are occasionally filled with green chlorite, throughout which are developed minute colourless garnets, but more frequently they are filled with a very fine-grained aggregate of carbonate, which also often contains fairly large quantities of colourless garnets. The latter reach a larger size than usual, being on an average 0.012 mm. to 0.025 mm. These garnets are not

always developed on such a large scale, and frequently they are entirely absent, the interstitial material consisting then of only fine grained carbonate. The areas that have developed these spherulitic structures frequently contain contraction cracks, some irregular in nature and some crossing the band at right angles to the bedding, but not extending beyond into the mudstone. These contraction cracks have been filled with secondary chlorite and silica, which have crystallized as fibres which are orientated at right angles to the walls of the cavity.[1]

Occasionally granular carbonate containing no spherulites has developed interstitial green chlorite, and in accordance with the presence of aluminous silicates and manganese carbonate, the colourless garnet is relatively well developed in these areas. Occasionally the garnets occur scattered throughout the massive dialogite in the absence of chlorite. On the whole the garnets tend to be more abundant towards the margin of the white or cream bands adjoining its junction with the normal mudstone. This indicates expulsion of the aluminous materials towards the exterior of the band in a similar manner as was noted in the case of the "irregular white blotchy developments" (p122).

The amount of magnetite contained in these carbonate bands is very small and tends to be limited to the external margins of the band

Mudstone with unusual gritty band.

A mudstone with an unusually heavy mineral-rich gritty layer occurred immediately below the ore in the Hendre locality, north-west of Moelfre. It is a relatively soft blue grey mudstone showing no lamination and having an uneven semi-conchoidal fracture. Microscopically it consists of an extremely fine-grained admixture of irregular grains of quartz, lath-shaped chlorite and sericite, minute reddish-brown garnets, some magnetite and occasional laths of tourmaline. The grain size is exceedingly small,

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[1] These contraction cracks form another important link in the chain of evidence for regarding the materials of sphaerodialogite bands as being originally colloidal. Since much of these bands consist entirely of carbonate material, it seems reasonable to believe that such large contraction cracks would only be possible if the carbonate itself were originally colloidal in form. The cracks would be formed by the dimunition in volume consequent on the dehydration of the gels due to crystallization of the carbonate. The lateral irregularity of these bands also supports the colloidal theory.

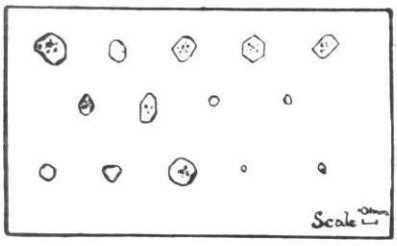

Fig. 9. Mode of occurrence of the minute reddish-brown garnets in the mudstones.

the equidimensional fragments ranging from 0.005 mm. to 0.010 mm. and the lath crystals from 0.010 mm. to 0.020 mm. long and from 0.002 mm. to 0.005 mm. wide. The quartz, forming 40 - 50 p.c. of the rock, is identical with that from the other mudstones, and both the chlorite and the sericite are also normal in character, being present in equal quantities forming 30 - 40 p.c. of the rock.

The garnets are abundant (forming 2 - 5 p.c.) and vary in colour from a deep reddish brown to a much paler amber brown. They vary in size from 0.002 mm. to 0.035 mm. being on an average 0.010 mm. They are euhedral, the majority of the crystals possessing good six-sided outlines in the section. Their refractive index is high and they stand out very clearly from the matrix. Ordinarily they are too small to show any definite characters in polarised light, but an occasional individual, isolated on the margin of the section, shows a perfect isotropic character. Their shape in section suggests the rhombododecahedron crystal form. They contain frequently, minute crystalline inclusions, usually concentrated in the central portion of the crystal. From their colour and in comparison with the colourless spessartite garnet, it is assumed that these probably contain a good proportion of almandine molecule. Colourless spessartite garnets, similar to those occurring in previously described mudstones, occur, but they are not nearly so abundant and are smaller in size.

The tourmaline is rare and euhedral and similar to that described above except that the grains are somewhat larger (0.04 mm. - 0.08 mm.).

The rock is slightly cleaved and this is shown in section by the marked tendency for the chlorite and sericite laths to occur, orientated at approximately 70° to the bedding, i.e, parallel to the cleavage.

Occurring in this rock is a thin band approximately 1/16th to 1/8th inch thick, which differs remarkably from the main portion of the rock as just described. It consists of about 60 p.c. of ordinary mudstone materials, throughout which occur uniformly scattered anhedral fragments of quartz, opaque minerals and an extraordinary abundance of "heavy" minerals. The upper and lower limits of this band are clearly marked from the mudstone above and below by the sudden increase of coarser

materials and the passage can be clearly delineated even under high powers. The quartz and the magnetite are of comparable size, varying from 0.03 mm. - 0.075 mm. The latter is undoubtedly allothigenous. Both these and the heavy minerals are subrounded to subangular in shape. The "heavy" minerals are the same as those recognized in the heavy residues of the grits: colourless to "dirty" zircon, subangular to rounded, 0.02 mm. - 0.07 mm.; colourless garnet 0.05 mm. - 0.07 mm.; anatase, pale blue, subhedral, sometimes showing slight evidence of regrowth and crowded with opaque inclusions, 0.04 mm. - 0.065 mm.; tourmaline, anhedral to subhedral, differing from the authigenous tourmaline of the mudstone by its large size, anhedral character, and presence of dense clouds of inclusions, 0.05 - 0.07 mm.; angular flakes of pale green epidote, some clear and some "dirty" 0.04 mm. to 0.08 mm.; and rarer irregular flakes of colourless muscovite.

The heavy minerals are not evenly distributed throughout the whole of the thin gritty band, but are concentrated in definite layers within it. These layers are very thin (0.8 mm. - 1.0 mm.) and within them the quantity of "heavy" minerals is remarkable. ranging from less than 20 p.c. to 40 - 50 p.c. of the whole layer. The position of the "heavy" mineral layer varies somewhat. Sometimes it has a medial position with regard to the whole gritty band, sometimes it occurs on one margin only, and when the band was thickest there were two layers one at either margin, which when they joined laterally formed a layer occupying the central portion of the band. Thus, there is no vertical concentration of the "heavy" minerals, say at the base of the gritty band according to gravity, and yet the quantity of heavy minerals present in the minor layers is so great that they could hardly have been formed by direct settling of material containing up to 40 - 50 p.c. of "heavy" minerals. The "heavy" minerals must have been evenly distributed throughout the whole gritty band, and the present "heavy" mineral layers are concentrates due to lateral sorting by water action.

General petrology of the mudstones.

The mudstones were formed by the settling down of very fine-grained detrital quartzose material, together with clayey aluminous

materials and manganese carbonate. The quartz fragments differ from those of the grits in size only, their grade being approximately 0.01 mm. or less. The aliminous materials were very fine-grained, and since the minerals formed by their recrystallization are the same as those formed in the matrix of the grits, it can be assumed that the aluminous materials in the mudstones were in the same form as those of the grits, which were regarded as being of a gelatinous colloidal nature. The manganese carbonate now exists in the mudstones in the minute globular bodies devoid of all crystalline structure, or in a much more finely divided interstitial condition, both of which are suggestive of a colloidal form originally. Moreover, the carbonate is obviously similar to that which forms the sphaerodialogite bands, and which for other reasons was regarded as being colloidal.

Thus the mudstones differ from the grits merely in the finer grained character of the detrital materials and in the greater abundance of dialogite, the aluminous material being more or less constant in character and amount. The finer grained character of the detrital fragments indicates a much slower rate of accumulation in the mudstones than in the grits. This in itself explains the much greater quantities of dialogite present in the mudstone. The manganese carbonate was being precipitated from solution, presumably in such a fine-grained dispersed nature as to be virtually colloidal. There would be very little variation in the rate of precipitation of the carbonate from time to time and consequently the quantity of carbonate which would be dispersed through grit several inches thick would be the same as that deposited within its time equivalent of mudstone, which would probably be a mere fraction of an inch in thickness. The actual proportion of dialogite in the mudstone would, therefore, be as many times greater than that in the grit as is the thickness of the grit greater than that of the mudstone. The ratio of the detrital quartz to the aluminous materials would remain approximately the same in the grits and the mudstones as long as the composition of the land mass being degraded remained the same. The difference in phase of the two-detrital quartz and the colloidal aluminous materials, merely results from the greater ease and the peculiar chemical manner in which the minerals

giving the aluminous materials break down. But the supply of both remains constant and continuous and so the proportions of the two in the sediment do not depend on the rate of degradation and sedimentation as was the case with the dialogite.

The striped banding, giving alternating laminae of relatively rich and relatively poor dialogite content, is regarded as being the direct result of a periodic variation, presumably, in this case, seasonal. Suppose a wet season were succeeded by a dry one: sedimentation would be greater in the wet season than the dry, and if precipitation of dialogite were more or less constant, the proportion of sediment to dialogite would be greater in the wet season than the dry; also the bands poorer in carbonate would tend to be slightly thicker than the others. Again suppose a cool season to be followed by a hot season and suppose sedimentation to be constant, precipitation of carbonate would be greater in the hot season than the cool, due to evaporation, with consequent formation of a carbonate rich layer during the hot season; but since the amount of sediment brought in both seasons was equal, the carbonate rich-layer would be thicker than the others, which is the reverse of the first case. Now as far as can be ascertained, the paler, carbonate-rich layers do not possess a general tendency to be either thicker or thinner than the darker bands with a less dialogite content. So that if this is a general rule the best explanation of the striped banding is by a combination of the suggestions made above: seasonal variation in sedimentation caused by the alternation of cool wet seasons with hotter drier seasons.

When ordinary sedimentation ceased the only material to be deposited would be the carbonate together with relatively small amounts of the colloidal aluminous materials, which by virtue of their nature, would remain in suspension much longer than the ordinary detrital quartzose fragments. These would settle under conditions largely governed by their colloidal nature and would give rise to the irregular developed white and cream carbonate layers described above, and to the "blotchy white carbonate developments" described in another section.

Conserable mineralogical change has taken place within the mudstones since they were deposited. These consist chiefly of recrystallization of the clayey materials, with the production of chlorite and sericite; reaction between dialogite, clayey materials and silica producing the authigenous minute garnet and recrystallization of excess iron as magnetite and less commonly as pyrite. The full significance of these metamorphic changes will be discussed at the end of the section on "The special developments of the Hendre locality".

The Special Mudstone Developments of the Hendre Locality (N.W. slopes of Moelfre).

From the exposures of the rocks associated with the manganese ore rendered accessible by the excavations of the Hendre Mines on the N.W. slopes of Moelfre, several variations from the normal type of "bluestone" mudstone were obtained. These fall into three types: A biotite-bearing mudstone; a massive garnet rock; and a calcite-muscovite bearing mudstone. Of these the first named is barely distinguishable from the normal "bluestone" mudstone in hand specimen, but both the other types differ very considerably and the divergence of mineral composition is obvious without resort to microscopic examination. That they are the stratigraphical equivalent of the normal "bluestone" mudstone is apparent from the examination of their field relations. They both follow the manganese ore band in a normal manner without break, and their relations with the succeeding strata is apparently identical as in the case of the normal mudstone. In addition although they show abvious microscopic differences their identity, especially in the case of the massive garnet rock is obvious, from the finely bedded character, similar to that of the normal mudstone.

These mineralogical changes are the result of localised differentiated metamorphism the significance of which will be discussed at the end of the section.

In order to show that the normal mudstone does occur associated with these rocks, a brief description of such an example will precede the details and discussion of the abnormal types:

Macroscopically this normal mudstone rock consists of a rapid alternation of darker and paler blue-grey bands. The laminae vary from 1/16th to 1/8th inch, with occasional layers up to 1/4 or 1/2 inch, the lamination being very even.

The darker bands consist of an exceedingly fine-grained admixture of quartz fragments, green chlorite and colourless sericite, dialogite, spessartite (colourless) and reddish-brown garnets and minute grains of magnetite, also very rare crystals of authigenous tourmaline. All the

constituents are of approximately the same grain size (0.01 mm). The quartz grains had an original subangular shape, which is now largely obscured by the recrystallisation of the aluminous minerals. The characters of the other minerals are similar to those occurring in the mudstones described in the previous section. The chlorite and sericite laths have a more or less parallel orientation, apparently in the plane of the bedding. The dialogite occurs in irregularly shaped globular bodies, 0.025 mm, often occurring in clusters scattered locally throughout the rock. The spessartite garnets are approximately 0.014 mm in size and form 2-3 p.c. of the rock. The minute reddish garnets occur associated with them in perfectly euhedral crystals with six sided outlines and form about 2 p.c. Magnetite, subhedral to anhedral, varying from 0.008 mm to 0.015 mm, occurs throughout and is probably detrital. The small euhedra of greenish brown tourmaline are of very rare occurrence.

The paler compact bands differ only in the greater relative abundance of the carbonate material, the amounts of quartz, chlorite, and sericite being correspondingly less. The increase in dialogite is also accompanied by a corresponding increase in the amount of colourless spessartite. In their extreme developments, these pale bands take on a character similar to that of the "ore" material, being composed essentially of an admixture of dialogite and spessartite.

Thus this is a typical mudstone similar in all characters to the normal "bluestone" mudstone described in the previous section.

Biotite - chlorite - spessartite - dialogite - quartz mudstone.

About half way up the exposures of the mines.

Macroscopic Characters.

A bluish-grey mudstone with a very regular striped bedding with the individual layers varying from less than 0.5 to 1.5 mm. and occasionally 3 mm +. The striped character is, as usual due to an alternation of lighter and darker materials. Occasionally interstratified layers of an almost white material occur. These are usually slightly thicker than the normal layers, and unlike them, they become irregular laterally.

They peter out and develop lenticular thickenings, the variations in thickness thus caused, being immediately compensated for in the mudstone layers above and below.

Microscopic Characters.

(a) the darker bands consist of a fine-grained inter-growth of quartz, similar to that of the "bluestone" mudstones already described; dialogite, in similar globular granules varying in size from 0.010 mm to 0.030 mm; colourless spessartite garnets, identical with those already described, reddish brown garnets, identical with, but not as abundant as, those described in the normal "bluestone"; magnetite, some relatively small, irregular grains (allothigenous) and some in euhedral octahedra up to 0.060 mm (authigenous); irregular and lath shaped crystals of chlorite, similar to those of general occurrence; and a greenish-brown mica.

The quartz makes up about 50 p.c. and the dialogite, chlorite and mica are about equal in quantity making up to 45 p.c. The magnetite is not abundant, neither are the garnets, the three minerals seldom forming more than 3-5 p.c. The colourless garnet tends to predominate over the reddish-brown variety. Very rare, small euhedra of authigenous tourmaline are observed. A notable feature is the complete absence of sericitic material. Its disappearance is coincident with the appearance of the new greenish brown micaceous mineral.

This occurs in irregularly dispersed aggregates of crystals varying in size from 0.020 mm to 0.080 mm, with an average of 0.030 - 0.040 mm. The individuals are sometimes platy fragments devoid of all shape, but they often show good tabular crystals with frayed and broken edges. The tabular crystals are elongated parallel to the direction of the good edges and they have a length : breadth ratio varying from 5 : 2 to 3 : 2. The basal section is doubtful but occasional isotropic fragments suggest a six-sided outline, though they are usually irregularly developed. The cleavage is perfect, though not abundantly developed, in one direction only: parallel to the length of the tabular crystals. In colour the mineral is greenish-brown with a well marked pleochroism, especially in

sections cut at right angles to the cleavage, and the greatest adsorption is parallel to the cleavage. The change in colour is from light greenish-brown or brownish green to an intense brown. Inclusions are practically absent. The refractive index varies from slightly above to distinctly above that of quartz and the maximum birefringence is approximately 0.040, the interference colours ranging up to red of the second order. Extinction is parallel to the cleavage traces, and the crystals are orientated with the cleavage traces parallel to the slower ray. Twinning is doubtful, parallel to the cleavage. Many of the crystals give a good interference figure which is biaxial and negative. The figures are best obtained on crystals showing no cleavage, indicating that, assuming the cleavage to be basal, the acute bisectrix X is normal to the 001 plane. The axial angle 2 V is small and dispersion is weak.

(These properties place the mineral undoubtedly in the biotite system and consideration of colour etc. suggests a species approaching phlogopite). The biotite crystals are orientated haphazardly with a slight tendency for the majority to be in planes approaching parallelism with the bedding. They are closely intergrown with the chlorite and there appears to be actual transition of the one into the other by the chlorite becoming darker in colour and developing a higher birefringence. Some of the tabular crystals even appear to consist partly of chlorite and partly of biotite with no sharp line of division between them. The relative proportions of chlorite and mica vary in different laminae, but a decrease in chlorite is usually accompanied by an increase in biotite and vice versa.

(b) The paler bands differ from (a) in the same way that the paler bands differ from the darker bands in the normal mudstone. That is, the proportion of globular dialogite is increased and there is a corresponding decrease in the other constituents. Bands representing all stages of transition between the end members of both types are observed.

(c) The irregularly bedded white bands are composed of massive aggregates of the dialogite granules largely to the exclusion of all other

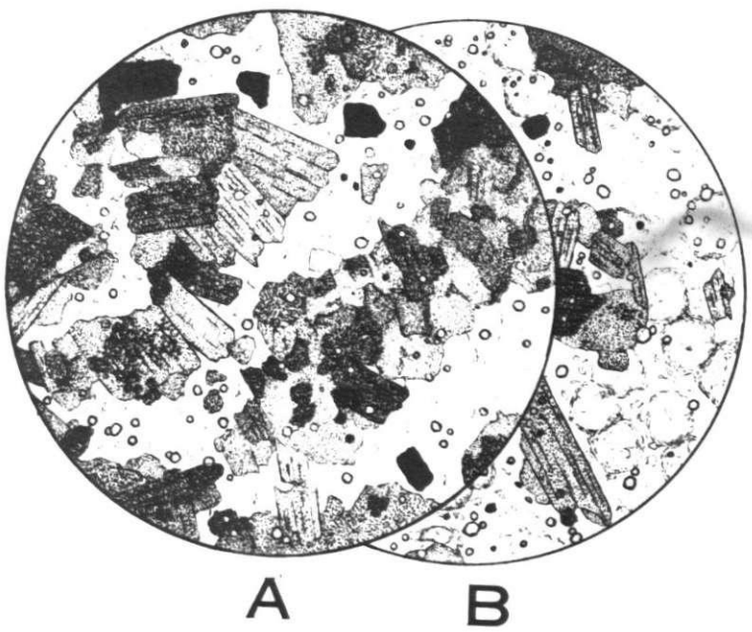

Fig. 10. The quartz-chlorite-biotite-spessartite-dialogite mudstone; Hendre Mines, N.W. of Moelfre.

A. The darker bands with abundant development of biotite. The accompanying minerals are: slightly recrystallized quartz colourless garnets, reddish-brown garnets (small black euhedra in diagram) and magnetite.

B. Paler bands with less biotite. Note the relative abundance of the globular granules of dialogite, Garnets, quartz, chlorite and magnetite are also present. Magnification × 375 diams.

materials, with the exception of the colourless garnets and these are not very abundant.

The transition between adjacent bands is rapid but a sharp line of demarcation can rarely be drawn. Macroscopically, a mudstone very rich in biotite and containing intercalated spherodialogite bands is similar to the normal "bluestone". That is, it consists of a regular alternation of darker and lighter bluish-grey materials. In thickness they vary from fractions of a millimetre to 1.5 - 2 mm. Occasionally is interbedded a more irregular layer of carbonate. These vary in thickness and one such band, (see Pl5 - fig1.) is "folded" into "overfolds" and monoclines" with all the folds pointing in the same direction, and is similar to the structure of the spherodialogite band (p. 117). Compensations are made for these deviations from the regular plane bedding in the mudstone immediately above and below, especially above, and the normal plane bedding soon reappears.

The minerals forming the mudstone are the same as those described above, with the exception that in most of the bands, both sericite and chlorite are now absent. That is the darker bands consist of an intimate mixture of quartz and biotite with lesser amounts of the globules of dialogite and subordinate colourless and reddish brown garnets, and the paler bands contain the same minerals but dialogite is relatively abundant. In some of the darker bands the biotite forms as much as 50 p.c. of the band and in such bands the amount of dialogite is very small. (See fig 6) In these bands also the reddish garnets are relatively more abundant than the colourless variety, while the absolute amount of magnetite present is also more. Thus the mica rich bands are relatively rich in iron, as contrasted with the dialogite rich bands.

The relatively thick irregularly bedded carbonate band is similar to those described under the mudstone with spherodialogite in the section on the normal mudstones. That is, it consists of massive aggregates of dialogite granules, occasionally developing a spherulitic structure with irregularly developed interstitial areas filled with chlorite and biotite and actually showing transitional developments of these minerals. The material pinched in between the limbs of the small overfolds was

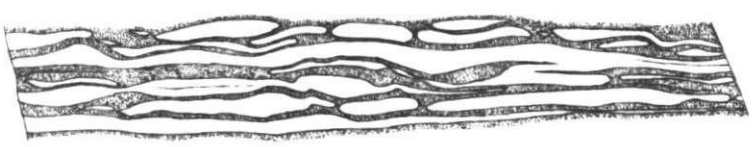

Fig. II "Bluestone with horny carbonate bands; Hendre Mines, N.W. slopes of Moelfre.

The carbonate bands possess a very irregular lithology with lateral thickening and thinning and formation of isolated lenticles having bluntly rounded terminations. Slightly more than natural size.

relatively free from detrital quartz. It now consists of compact aggregates of biotite, some bright green chlorite, often showing transition to mica, abundant colourless garnets near the junction with the carbonate band in particular, and a zone of abundant reddish-brown (often nearly black) garnets developed in a zone between the colourless garnets and the biotite. The cracks traversing the band run at right angles to the bedding, are up to 1 mm thick and are filled with fibrous chalcedonic silica with subordinate intergrown fibrous green chlorite, the fibres being orientated at right angles to the walls of the crack. They are contraction cracks, and are one of the important reasons for believing that these carbonate bands were originally of a colloidal nature.

The relationships of the biotite in these mudstones is shown in Fig. 10 A specimen of "Bluestone" taken from immediately above the ore band has the following characteristics: It consists of a regular alternation of darker type blue-grey mudstone and paler purplish cream bands. The latter are somewhat 'flinty' but are not so hard as the ore band proper. The bedding of the mudstone is of similar type tothat described in the typical 'bluestones'. Sometimes the paler bands are developed on a larger scale - in bands 1.5 mm to 2.0 mm. These show irregular bedding when traced laterally. They frequently occur in groups of five or six bands separated only by thin layers of the dark mudstone. These bands, thicken or thin laterally, end abruptly with blunt rounded ends, and frequently break down into a series of bluntly ended lenticles. (see fig. 11). A notable feature is the way in which compensations are made for these thickness variations. For example, a group of five or six of these layers, taken together, form a band say, 12 -14 mm thick and this thickness remains very constant when traced laterally, and this in spite of the various irregularities in the individual layers themselves. Thickening, thinning, or absence in one of the bands is immediately compensated for by a thinning or a thickening in the mudstone layer above or below. Excess of thickening of one band may cause lenticular development in the band above with the lenticles resting on the thinner portions of the band below. These "flinty" bands are very clearly marked off from the mudstone materials above

and below.

Under the microscope the darker mudstone bands are similar to those described first under this heading. They contain quartz, biotite, small amounts of chlorite, colourless and reddish brown garnets, magnetite and dialogite. The ~~sericitic~~ mica is abundant.

The 'flinty' bands show a similarity to the 'ore' material: they consist of an admixture of colourless garnets and granules of dialogite, the latter predominating. Many of the paler bands show the ordinary carbonate rich type of mudstone lithology, with predominant dialogite and spessartite and less abundant quartz, biotite, and reddish brown garnet.

Even under the high powers of the microscope the passage from the 'flinty' bands into the mudstone appears very abrupt and can be delineated.

The garnet-quartz rock.

All the specimens obtained in the Hendre locality were from the same area, which is situated near the lower end of the workings. Similar rocks, though they are not developed to the same absolute scale were noted in the middle region of the Cwm Mawr workings, North of Cwm Bychan.

Macroscopic Characters. (see Pls fig 2.)

In general appearance they have a superficial similarity to the ordinary bluestone, i.e. they possess the peculiar, "striped" thinly-bedded lithology. Whereas the ordinary "bluestone" is relatively soft (it can be easily scratched with a knife) and friable, this rock is much more compact and it is very hard and flinty, being much harder than a knife. It has an uneven, semi-conchoidal fracture and there is no cleavage. The rock has a very "hornstone"-like character. In colour it has also suffered change. Instead of consisting of a regular alternation of dark and paler blue-grey material, the colour of the rock is generally lighter and it consists of alternations of very pale greenish grey and somewhat darker greenish-grey bands, some having a slightly purplish tinge. The bedding, on the whole, is rather regular, but occasionally the beds show signs of much crumpling due to lateral pressure and

movement. This is well shown in Pl. 4 figs. 1&2, in which case differential weathering of the paler, hard bands and the softer darker bands has brought out the detail of this minor crumpling very well. Some specimens show a slight tendency to disharmonic crumpling, with bands, which are well folded succeeded by beds which are not so intensely crumpled.

Occasional irregular lenticular masses occur which are darker and more siliceous than the ordinary banded rock; these are especially developed as pinched out lenticles among the crumpled portion.

This flinty type of rock occasionally appears to pass by transition into the calcite-muscovite baring rock to be described below.

Microscopic Characters.

The rock consists essentially of colourless garnet and quartz. The garnets vary in size from 0.004 mm to 0.014 mm; i.e. they are of the same size as the ordinary colourless garnets described from the less altered mudstones. Throughout both the pale and the slightly darker bedded materials, this garnet makes up by far the predominant portion of the rock. In the paler bands it comprises approximately 90 p.c. of the rock, the rest being made up chiefly of quartz. In the slightly darker bands the amount of colourless garnet falls to 80 p.c. and the quartz is relatively more abundant. In addition the slightly darker bands often contain a small amount of intergrown chlorite. This is of a very pale green type and is only feebly pleochroic; it occurs in slender fibres and laths and on account of its paleness is not easy to distinguish. It possibly contains less iron and more magnesium relatively than the brighter pleochroic variety of the normal mudstone. It gives ultra-blue polarisation colours and may be related to penninite. Thus the paler bands of this rock correspond to the paler bands of the normal "bluestone" and the darker to the darker respectively, since the darker bands show relatively more quartz-ose and aluminous materials than the paler bands, and the paler bands more manganese (in the form of spessartite).

The quartz has been recrystallised and bears an interstitial relationship to the garnet. Owing to the great preponderance of garnet, the major portion of the rock remains dark when the field is revolved

between crossed nicols, and the area of isotropic material tends to be somewhat greater in the paler than in the slightly darker bands.

Magnetite occurs and presumably represents the original euhedra of the "bluestone". It does not appear to be as euhedral now and marginal solution is suggested.

Reddish-brown garnets occur sporadically, representing the original content of the "bluestone". They are not abundant and some solution of them might have taken place during the regeneration of the colourless garnet. They have the same size and characteristics as described in the normal mudstone.

The dark, irregular, lenticular developments consist of a mosaic of regenerated quartz with relatively abundant chlorite of the very pale, feebly pleochroic type, regenerated dialogite, and thinly dispersed colourless garnet. The constituents are closely intergrown and have a relatively large "grain", approximately 0.1 mm. The dialogite has recrystallised into irregular crystals intergrown with the quartz to form a mosaic. Good rhombohedral cleavage is developed, and it is distinguished from calcite by virtue of its higher birefringence.

The Calcite-Muscovite-Chlorite Rocks.

The rocks concerned were noted in one locality only - in the open trench workings in the lowest of the Hendre Mines on N.W. slope of Moelfre 1/4 ml. S.E. of Cil Cychwyn Farm.

From its position with regard to the "ore" band, these rocks must be regarded as the equivalent of the normal "bluestone". In appearance, however, it is considerably different, and the fine grained matrix frequently possesses characters showing passage to the "hornstone"-like garnet-quartz rock.

In colour the rock is a dark greyish-green, the intensity of the colour varying slightly in different bands. The original thinly bedded, striped, character of the "bluestones" is still discernable, though recrystallisation has made it less obvious. The rock now consists of an alternation of dark greenish-grey bands and lighter greyish green bands. The latter are frequently very hard and very compact, have an uneven semi-conchoidal fracture, and are similar to the

garnet-quartz rock. The darker bands are not so hard, and they have a coarser and less compact nature. Usually throughout the latter is developed abundant coarsely crystalline mangancalcite. These crystals vary in size from 2-4 mm and are frequently well developed in bands coincident with the bedding of the rock, the bands varying from 4 - 30 mm in thickness. Sometimes within the thicker bands in which the calcite is developed it is mainly concentrated along minor layers parallel to the bedding. The crystals only very rarely appear within compact "horny" bands.

Often the darker, coarser type of material is developed in layers practically free from the mangancalcite crystals, and interbedded with layers of calcite bearing rock and the hard compact layers.

A specimen consisting of a thickness of 23 cms of rock was made up as follows:

1. An incomplete portion consisting of dark, compact, soft rock with abundant twinned scalenohedra of mangancalcite. Original bedding largely obscured 2.5 cms.

2. Followed by 4 cms of calcite free rock. A relatively well-banded portion consisting of alternation of dark, soft, compact mudstone; darker, soft, more coarsely crystalline mudstone, and paler compact "horny" garnet-rock. The last type occur in persistent layers, but the first two are irregular, one type tending to merge laterally with the other.

3. Dark relatively compact rock with calcite scalenohedra 1.2 cms.

4. Thinly bedded alternations of soft, compact, mudstone and soft more coarsely crystalline mudstone with subordinate "horny" layers, and a few, laterally impersistent developments of scalenohedra bearing layers, 2-4 mm. The whole being 3.2 cms thick.

5. 5.5 cms consisting chiefly of "horny" type, with minor intercalations of darker compact material and irregular developments of the more coarsely crystalline type.

6. A layer 1 cm thick of "more crystalline" soft mudstone with moderately abundant calcite crystals.

7. About 2 cms of calcite-free mudstone of the "coarser" type

Fig.12 Calcite-Muscovite rock; Hendre Mines, N.W. of Moelfre.

General aspect showing the relationships of the twinned scalenohedra of mangancalcite in section. Magnification × 5 1/2.

with intercalations of the "horny" garnet layers.

8. 4 cms of dark compact mudstone material with three well developed layers of calcite crystals 0.8, 1.2, 0.6 cms thick respectively. There are minor developments of the more crystalline material, especially in the calcite bands themselves, but no "horny material is present.

Weathering.

The mangancalcite first becomes coated with a veneer of brownish-black pyrolusite, and finally dissolves away entirely leaving triangular cavities lined with the same material. The cold matrix is more resistent than the calcite-crystals and often remains unaltered after the solution of the calcite. It ultimately breaks down leaving a brownish coloured, soft, powdery material consisting of iron and manganese oxides with silica.

Microscopic Characters.

(a) The calcite-bearing bands. The rock consists of large porphyroblasts of mangan-calcite set in a very fine grained matrix consisting essentially of chlorite with subordinate colourless garnet, quartz, and a fair amount of relatively large crystals of colourless muscovite.

The mangancalcite occurs in scalenohedra, up to 4 mm and sometimes more in length, which have a characteristic triangular outline in section. Almost invariably these scalenohedra are twinned (figs. 12 and 13), the twin plane being the $10\bar{1}1$. Quite often this twinning is of the simple type[1] consisting of two half-scalenohedra twinned on $10\bar{1}1$. Frequently, however, each individual is represented by a complete crystal, the twinning plane still being the $10\bar{1}1$, the resulting twin appearing as a cruciform interpenetration form (fig 13). The angle between the vertical axes of the twinned crystals varies in section up to nearly 90°. In addition to these twin-forms, the individuals freqnently possess twin laminae. These can be separated into two forms:- (a) twin laminae parallel to the main twinning, i.e. parallel to $10\bar{1}1$, and (b) twinning parallel to $0\bar{2}21$. The whole crystal is but rarely made up entirely of a succession of twin laminae, the usual occurrence being of isolated laminae within the main crystal.

1. See fig. 448. Dana's Textbook of Mineralogy, Ed. by W. E. Ford. New York, 1932. p. 189.

As usual the twinning shows up more clearly between crossed nicols.

The margins of the crystals are clearly defined, though the apical coign maybe broken away or irregularly frayed. The relief is high and the birefringence extreme, the polarisation colours being of the fourth order. Extinction is parallel to the principal axis of the crystal, i.e. a line bisecting the apical angle of the crystal in section. The interference figure is uniaxial and negative.

The crystals have no particular orientation within the rock and they lie in all directions, in sections cut both parallel to, and transverse to the bedding. Thus their orientation bears no relationship to any possible direction of stress.

The crystals contain numerous inclusions of the fine grained matrix material, which under low powers appear as a 'mushy' discoloration of the crystal. The thin banding of the mudstone is discernable under the lower powers, and the bands are seen to be carried across the crystal as variations in the amount of included matter. Thus, if a pale, or a darker band be seen to abutt on a crystal, the darker band is carried across the crystal as a band richer in included matter than that portion corresponding to the paler band. This expression of the original minor binding of the rock within the crystals themselves, shows that the crystals have had their origin "in-situ".

The inclusions when examined under high power are seen to consist of: laths and irregular crystals of pale green, feebly pleochroic chlorite (identical with that in the matrix); not very abundant colourless garnets having the same properties and dimensions as those occurring in the matrix of the normal mudstone; and a more indefinite mineral occurring in irregular granules, somewhat similar to the globular granules of dialogite occurring in the unaltered mudstone(a conclusion which is also supported by their slightly higher birefringence). Also larger crystals, relatively infrequent, of muscovite, identical with that in the matrix (see later) occur. These may be totally included within the mangancalcite crystals, or they may have a kind of ophitoblastic relationship, being partly within the crystal and partly within the matrix (see fig. 38). Small rare magnetite crystals also occur included in the mangancalcite

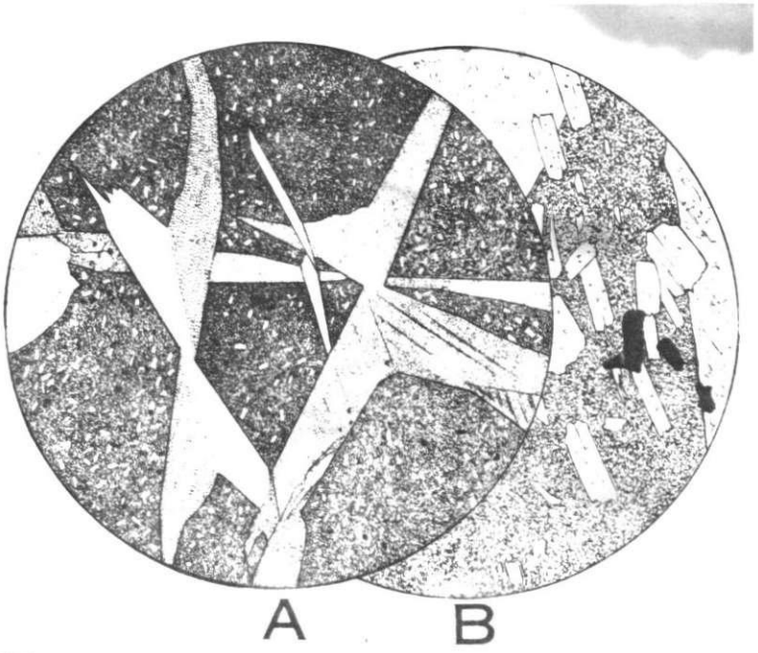

Fig. 13 Calcite-muscovite-chlorite rock; Hendre Mines, N.W. slopes of Moelfre.

A. Cruxiform inter-penetration twins of mangancalcite scalenohedra are set in a fine-grained matrix of chlorite, quartz, muscovite, magnetite and colourless garnet. The small rectangular crystals are of muscovite and the black mineral is magnetite. Mangification × 15 diams.

B. The muscovite has an ophitoblastic relationship to the calcite and a porphyroblastic relationship to the fine-grained matrix of chlorite, quartz and garnet. Note the tendency for parallel arrangement of the muscovite. Magnification × 40 diams.

(fig. 13A). The Matrix consists of a massive aggregate of chlorite laths, with varying small amounts of interstitial quartz, fairly common colourless garnets, moderately abundant, but varying from layer to layer, colourless mica, and not irregular grains of magnetite.

The chlorite occurs as individual lath shaped crystals, sometimes with indefinite, and sometimes with pseudorhombohedral, terminations. They vary in size up to 0.05 mm and have a length : breadth ratio of 7 : 1 to 3 : 1. They are pale green and almost non-pleochroic. They possess good relief; the refractive index being moderately well above that of Canada balsam. The birefringence is very low, the polarisation colours being ultra blues. Extinction is approximately parallel to the lengths of the laths. The chlorite appears to be identical with that developed in the garnet-quartz rock (Q). The laths have a more or less parallel orientation in a plane approximately at 30° to the bedding.

The quartz is recrystallised and has an interstitial relationship. The garnets are small 0.005 mm - 0.014 mm and are identical in characters and approximately in quantity to the colourless spessartite garnets of the normal mudstones.

The colourless mica occurs in tabular crystals with irregular and broken terminations. The smooth edges, forming the length of the tabular crystals are parallel to the only cleavage (001), which is well developed. (Fig. 13B). In size they vary from 0.12 mm X 0.045 mm to 0.03 mm X 0.012 mm.

The refractive index varies from slightly above to below that of the chlorite. The birefringence is strong, the interference colours usually being of first order reds or blues in sections showing good cleavage, but extending up to second order reds in other sections, thus indicating a birefringence of approximately 0.035 to 0.040. Extinction is parallel to the cleavage traces. The crystals are orientated with their cleavages parallel to the slower ray. The interference figure is biaxial and negative and its form indicates a fairly high axial angle and a somewhat weak dispersion. All these properties agree with those of muscovite.

The amount of muscovite present varies, some bands possessing

scarcely any, and others developing it abundantly. They are usually orientated in all directions, but in one section there was a marked alignment of the crystals parallel to the plane in which the chlorite is orientated, with occasional crystals developed more or less at right angles.

The magnetite crystals are residual. They are irregular in shape and appear to be original euhedra, which have suffered some degree of solution on their margins, removing the sharp edges and coigns.

(b) The soft, compact, dark material without calcite porphyroblasts. This is very similar to the matrix material just described, that is, it consists chiefly of pale green chlorite, with fairly frequent colourless garnets and interstitial quartz with relatively large crystals of muscovite, and some residual magnetite. The amount of muscovite as before varies from layer to layer. These layers are 1.0 - 1.5 mm thick on an average. In hand specimen the layers containing the abundant mica are slightly paler in colour than the layers in which it is relatively poorly developed. In the layers containing less muscovite the amount of small garnets is increased.

(c) The paler green hard compact layers - also devoid of the calcite porphyroblasts. These consist essentially of the colourless garnets and interstitial green chlorite. Both minerals have the usual characteristics. The garnet varies in quantity and various bands show complete passage to the soft compact rock of (b); in the true hard bands they form 50 - 80 p.c. of the whole and they pass by transition to the hard garnet quartz rock. Several bands bordering on true muscovite bearing bands show shapeless fragments of a colourless mineral having a relatively high birefringence and these suggest muscovite which is in the process of being broken down to form the massive garnet rock.

(d) The dark, soft, "more crystalline" type of material. These bands consist of very abundant tabular and platy crystals of muscovite, with interstitial pale green chlorite and quartz with some ill-developed porphyroblasts of mangancalcite. The muscovite has a porphyroblastic relationship to the much finer grained closely intergrown chlorite and quartz and colourless garnet is scattered more or less uniformly throughout the whole, being included in the muscovite and the mangancalcite.

Magnetite occurs, but is not abundant and it was the same anhedral character as that indicated above.

The muscovite occurs in tabular and platy crystals, with an approximation to uniform size in each band, but varying from layer to layer. In some layers they average 0.04 mm - o.08 mm, in others 0.06 to 0.11 mm, and rarely 0.25 mm long. In quantity they vary from forming 30 p.c. to forming 75 p.c. of the total. Their optical properties are described above.

The amount of quartz varies, being sometimes greater in quantity than the chlorite, but usually less. The calcite crystals are not abundant and tend to be obscured in hand specimen. They are apparently later in formation than the muscovite, for they are penetrated by the latter giving an ophitoblastic texture. The colourless garnets often form as much as 10 p.c. of the rock.

The Metamorphism of the Mudstones.

I. Production of the Normal Mudstone Type.

These are typified by the normal "bluestone" mudstones described on pp.54-67. They consist of intimate admixtures of the following minerals: quartz, chlorite, sericite, dialogite, colourless garnets, reddish-brown garnets, magnetite, and tourmaline. The rocks when they were laid down consisted of quartz as minute detrital fragments, colloidal clayey and siliceous materials, and manganese carbonate formed from solution (pp.64-67). It follows, therefore, that the minerals recorded above, with the exception of quartz and dialogite, have resulted from chemical reaction, chiefly among the alumino-siliceous colloidal materials of the original sediment. Owing to the marked uniformity of this normal mudstone type over the whole area, these mineral changes are regarded as having been induced by a general regional metamorphism. This metamorphism was the result of a uniform increase in pressure and temperature caused by the increasing weight of superimposed materials as the rocks concerned sank beneath the Caledonian Geosyncline.

The metamorphism was essentially low grade and is characterized by the recrystallization of the alumino-siliceous colloidal materials to form chlorite and sericite, the actual proportions of these two minerals varying according to the original composition of the alumino-siliceous mixture. The general metamorphism of these rocks, therefore, corresponds to the first or chlorite zone of normal regional metamorphism as described by Barrow,[1] Tilley,[2] Goldschmidt[3] and others. In addition, the extremely fine-grained character of these minerals indicates that the metamorphism belongs to the outside limit or lowest grade of the zone.

The chlorite resulting from this first recrystallization is very uniform in character, there being practically no variation in colour or optical properties throughout the normal mudstones of the whole area. This

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1 "On an Intrusion of Muscovite-biotite Gneiss in the South-eastern Highlands of Scotland, and its accompanying Metamorphism." Q.J.G.S. Vol.XLIX. (1893). pp.330-58. and : On the Geology of Lower Bee-Side and the Southern Highland Border". Proc. Geol. Assoc. Vol.XXIII. (1912). pp.274-90.

2 "Some Mineralogical Transformations in Crystalline Schists." Min. Mag. Vol.XXI. (1926). pp. 34 - 46

3 Die Injektionsmetamorphose im Stavanger Gebiet. Vidensk. Skr. 1920. (No.10). 1921.

does not seem to be true of the sericite, which varies in colour from colouress to very pale green and in which there are apparent irregularities of optical properties (especially birefringence). Consequently it is suggested that the chlorite forms first, of a constant nature, with the sericite resulting from the residual material and varying slightly according to the nature of that residue. The exact nature of the sericite is unknown.

Owing to the fine-grained nature of the chlorite and its intimate admixture with other materials of approximately the same specific gravity it was impossible to separate any from mudstones for analysis. However, the similiarity of the optical properties and colour etc., indicate that the chlorite of these mudstones is identical with that analysed in the sphaerodialogite band (p.124). This analysis is again stated and comparison made with chlorite from other low grade metamorphic rocks:

	I	II	III
SiO_2	21.50	24.8	24.7
Al_2O_3	27.03	18.3	19.1 (+TiO_2)
Fe_2O_3	0.58	7.3	5.2
FeO	25.01	25.2	33.0
MnO	3.17	1.2	
MgO	9.21	10.1	4.3
CaO	2.32	-	4.4
H_2O	11.18	12.9	9.3
	100.00	99.8	100.0

I. Chlorite from sphaerodialogite-rock, St. John's Church, Barmouth.

II. Chlorite from the Stavanger District.[1]

III. Chlorite from the quartz-garnet-chlorite-phyllite, east of Cleve Valley, Duchess County, New York.[2]

It will be noted that the chlorite of these rocks is much richer in Al_2O_3, while Fe_2O_3 is almost negligible. There is, however, a considerable ferric iron content in the rock (see anals. p. 98), a factor which is

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[1] Goldschmidt, V.M: Vidensk. Skr. 1920 (No.10). 1921. p.59.

[2] Barth, T.F.W: loc. cit. p.795

represented mineralogically chiefly by magnetite. Sufficient alumina was apparently present to satisfy the requirements of the chlorite being formed, and what iron there was available in the ferric state merely recrystallized to form magnetite. (This ferric iron probably represents the original hydrated iron oxide (limonite) content of the clayey materials). The crystallization of the magnetite occurs at this early stage,[1] as, also, does the crystallization of any pyrite that may be present.[2]

The garnet associated with these rocks is of special interest. Normally garnet is a result of metamorphism of a rather high grade and follows the appearance of biotite in the normal sequence of mineral production. This has been proved by Barrow,[3] Tilley,[4] Goldschmidt[5] and others in the metamorphic zones of the Highlands of Scotland, and the South-Norwegian Mountains. In the present case, however, abundant minute garnets are noted in the quartz-chlorite-sericite rocks, with no associated biotite whatsoever. Thus the order of biotite-garnet crystallization is reversed and the garnet precedes biotite. In addition, it is hardly possible to separate the formation of the garnet as a marked stage succeeding the chlorite zone, in this case, and it seems that the garnet must really be regarded as part of the chlorite zone itself. Of course, theoretically, the formation of the garnet must tend to postdate the chlorite, and this seems to be borne out by the fact that mudstones (and grit matrices) do occur in which only very small quantities of garnets are developed, while in others they may be very prominent. It thus appears that garnets can be initiated under special conditions in the very earliest stages of metamorphism, tending to follow immediately on the formation of the chlorite and sericite.

Many instances are now recorded of garnet occurring in chlorite bearing rocks prior to the formation of biotite. In every case, however, the garnet occurring was of a particular type, and notable for a large manganese

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1 See also: Harker, A: Metamorphism. (1932). p.210

2 See pp. 110-116

3 loc. cit.

4 loc. cit.

5 Die Kalksilikatglimmerschiefer des Trondhjems Gebiets. Videnskab. Skr. 1915.

content. Goldschmidt[1] records quartz-muscovite-chlorite-garnet phyllite succeeding quartz-muscovite-chlorite-phyllite in the Stavanger district, the garnet containing 12.28 p.b. MnO and 4.23 p.c. CaO. Tilley[2] notes garnet developed immediately after the lowest grade, represented by quartz-muscovite-chlorite-albite rocks, in the Start area. The garnet "is an almandine containing 5.5 p.c. of manganous oxide, corresponding to a spessartite content of 12.8 p.c." Phillips[3] records minute spessartite garnets in the chlorite-phyllites of N. Cornwall, and they contain 12.5 p.c. of MnO; again no biotite was recorded. H. Williams[4] describes spessartite garnets in a grit band among the Talgan lavas of Snowdon associated with chlorite and green biotite. Garnets containing 0.35 p.c.- 1.23 p.c. MnO are recorded from the low grade quartz-garnet-chlorite schists of Duchess County, New York[5]. Tilley[6] also notes that the presence of manganese promotes the formation of garnets in contact zones of pelites.

The colourless garnets in the present case were far too small to isolate, but optically they are almost identical with the minute garnets occurring in the manganese ore, of which analyses were obtained. These contained 36-39 p.c. of MnO corresponding to 85-90 p.c. of the spessartite molecule. It is thus indicated that the colourless garnets of the mudstones contain a very high percentage of manganese.

So once more the theory that manganese, present in significant quantities, leads to a much earlier development of garnet than would otherwise be the case, is borne out. Two analyses (I and II p.) of the normal chlorite-sericite mudstone bearing garnet gave 12.23 p.c. and 13.59 p.c. of manganous oxide respectively. Only a relatively small proportion of this, however, enters into the composition of garnet, the bulk remaining in the form of dialogite. Thus, it must be that the very large amounts of manganese

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[1] Vidensk. Skr. 1920. (No.10). 1921. p.60ff.

[2] "The Petrology of the Metamorphesed rocks of the Start area." Q.J.G.S. LXXIX. (1923). p.198.

[3] "Metamorphism in the Upper Devonian of N. Cornwall". Geol. Mag. LXV. (1928). p.550.

[4] "The Geology of Snowdon (North Wales). Q.J.G.S. LXXXIII. (1927). p.361.

[5] Barth, T.F.W.; loc. cit. p.785.

[6] "On the garnet in the pelitic contact zones". Min. Mag. XXI. (1928). p.50.

present in a very readily available form[1], are answerable for the very early appearance of garnet. The garnets here appear to come on the scene at an earlier stage in the chlorite zone than hitherto recorded. This indicates that the ease of formation of these garnets may be proportional to the amounts of available manganese present.

The reddish-brown garnet present in all these mudstones is regarded as being an almandine form rich in the spessartine molecule. It is only present in the mudstones (and grits) and is absent from the "ore" material. Its presence is, therefore, linked with the presence of available iron in the alumino-siliceous materials of the mudstones, and its absence in the "ore" with the deficiency of available iron. The fact that, as far as the mudstones are concerned, the reddish-garnet is always present in approximately constant amount, whereas the colourless form varies considerably from being virtually absent to being very abundant, is interpreted as indicating that the reddish garnet tends to precede the colourless form in crystallization. It may be that a small approximately constant amount of FeO always combines with MnO in forming the first garnets, that this is soon used up, and all garnet forming after this is very rich in manganese and colourless.

The garnet would be formed by the interaction of chlorite and sericite with manganese carbonate and silica:

$$2Al_2O_3.5(MgFe)O.3SiO_2.5H_2O + K_2O.(Mg.Fe)O.2Al_2O_3.7SiO_2.2H_2O + 6MnCO_3 + 2SiO_2$$

(chlorite) (sericite) (dialogoite)

$$= 4[3(MnFeMg)O.\ Al_2O_3.\ 3SiO_2] + 7H_2O + K_2O + 6CO_2$$

(garnet)

or more simply:

$$Al_2O_3 2SiO_2.2H_2O + 3\ MnCO_3 + SiO_2 = 3MnO.\ Al_2O_3.\ 3SiO_2 + 2H_2O$$

(clayey material) (dialogite) (spessartite)

With regard to the formation of tourmaline in these mudstones: it occurs sporadically and in very small amounts, the very minute euhedrel crystals being obviously authigenous. The lower grits of the Arenig (Plas-y-Nant) Beds of Snowdon are extensively tourmalinized. Williams states

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[1] It is much easier to obtain manganeous oxide (MnO) from manganese carbonate than from pyrolusite or any of the more complex manganese silicates. MnO_2 etc. are very stable but $MnCO_3$ readily decomposes to $MnO + CO_2$.

that "the cause of their tourmalinization is unknown, but it operated after the sediments had been disturbed by thrusting", and adds in a footnote, that "there is no certain record of tourmaline in the Mynydd Mawr 'riebeckite-granite' a mile and a half distant, so that the tourmalinization may be unconnected with that intrusion".[1] Concerning similar rocks at the same horizon near Llanberis, Fearnsides[2] remarks: "The tourmaline is not clastic but has been formed in situ from the feldspathic ground-paste of the grits or flags... There has been much thrust faulting along the unconformity but no large intrusive mass of ignous rock has been observed within five miles of the locality". In connexion with the same rock, Harker[3] states: "tourmaline has sometimes been formed in a quartzose grit.... at a distance from any ignous intrusion. This, it would seem, is to be explained only by the bodily introduction of tourmaline, or at least of the sum total of its constituents in some form." In Duchess County, New York, tourmaline occurs scattered over the whole area in all kinds of rocks. "It seems worthy of special emphasis", Barth states, "that it extends into the fossiliferous rocks of Palaeozoic age, thus testifying to a low grade pneumatolytic metamorphism far away from the granitic intrusions, which undoubtedly were the source of the pneumatolytic solutions"[4]. Harker[5] also states that "tourmalinization may indeed be found at a considerable distance from a granite contact, but only in proximity to tourmaline-quartz veins, which mark the channels of supply."

Thus the consensus of opinion regarding anthigenous tourmaline in sediments is that it is always of pneumatolytic origin even though it occurs far away from the nearest possible source of supply. While this view is favoured in the present instance, it does not seem impossible that these small amounts of tourmaline may be the result of recrystallization of

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[1] Williams, H: loc. cit. p.344-5.

[2] "The Tourmaline Rocks of Cwm Dwythwe, near Llanberis (North Wales)". Rep. Brit. Assoc. (1908). p.704.

[3] "Metamorphism" (1932). p.121-2.

[4] loc. cit. p.792.

[5] op. cit. p.119

materials resulting from the degradation of allothigenous tourmaline. The grits contain abundant detrital tourmaline of a like colour to this authigenous type, and this must be present in some form in the mudstones. The B_2O_3 could not have been entirely lost on degradation. However, rare greenish-blue tourmaline is recorded in occasional quartz veins that traverse these rocks, and these quartz veins may have been the ultimate source of the tourmalinizing solutions.

Thus the present normal mudstones are regarded as being the result of low grade metamorphism, corresponding to the chlorite zones of various authors. The metamorphism is regarded as being depth metamorphism, with increase of temperature and pressure, the latter uniform and vertically directed, shearing forces being absent. These lower Cambrian rocks, during the course of Lower Palaeozoic time, were covered with tremendous thicknesses of Upper Cambrian, Ordovician and Silurian before final uplift took place. The weight of this superimposed material is regarded as having been sufficient to induce this lower grade metamorphism.

II. The Special Types of the Hendre locality.

Special interest is attached to the rocks of this locality because of the occurrence of minerals indicative of higher grades of metamorphism than that indicated by the normal mudstones.

The first stage of this increased metamorphism is noticed in the biotite-chlorite-spessartite-dialogite-quartz rock ~~of B~~ (pp.69-74). This differs from the normal quartz-chlorite-sericite-spessartite-dialogite mudstone by the appearance of biotite and the gradual disappearance of sericite. All grades of transition are noted, from rocks containing chlorite and sericite with small amounts of biotite, through rocks with abundant biotite, some chlotite and no sericite, to rare bands containing predominant biotite and neither chlorite nor sericite. These rocks indicate the commencement of the biotite zone of metamorphism, which normally follows the chlorite zone, in normal regional metamorphism (see Barrow, Tilley and Goldschmidt in works cited). The characters of the residual chlorite are exactly the same as those of the chlorite in the normal mudstone, and the advent of biotite is unaccompanied by any recrystallization of the other constituents. It thus seems that the formation of the biotite is only a slight metamorphic advance on the normal chlorite-sericite stage. The advance appears to be so slight that it is reasonal to conclude that the

biotite zone in this case is initiated at a much earlier stage than in the case of normal regional metamorphism. Harker[1] states that when metamorphism takes place under conditions of deficient shearing stress, as compared with the intense shearing of normal regional metamorphism, the lower grades are characterized by the relatively early appearance of biotite and "biotite may figure in rocks which still retain much of their original clastic structure". F.C. Phillips[2] states that "one of the earliest changes (in the chlorite zone) is the production of a green-brown biotite". It is noteworthy that the biotite formed in the present case is a distinctly green-brown variety, and it appears that such a form is characteristic of the first stages of the development of biotite. Tilley[3] in discussing the progressive metamorphism in the Southern Highlands remarks: "It is of consequence to note here that the common brown biotite is now in question. A green to brownish green pleochroic biotite arises at an early stage of metamorphism."

The size of the individual crystals of biotite in these rocks is so small and they are so intimately mixed with quartzose and chloritic materials, that it was found impossible satisfactorily to separate any for analysis. Unfortunately, therefore, no information is forthcoming regarding the exact compsoition of the biotite formed.

Comparing analysis III and IV (biotite bearing rocks) with those of I and II (normal chlorite-sericite mudstones) it is noted that they have approximately the same bulk chemical composition. The changes resulting in the formation of biotite, therefore, can be reasonaly assumed to be merely mineralogical transformations, and not the result of introduction of any material from outside. Concerning the nature of these transformations two facts are noteworthy: the appearance of biotite is accompanied by a corresponding decrease in the amount of sericite; the chlorite in many instances was seen to be actually changing to biotite, individual crystals not infrequently appearing to be composed of both normal green chlorite and green-brown

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1 op. cit. p.230.

2 "Some Mineralogical and Chemical Changes induced by Progressive metamorphism in the Green Bed group of the Scottish Dalradian." Min. Mag. XXII. (1930).p.250.

3 "Metamorphic Zones in the Southern Highlands of Scotland." Q.J.G.S. LXXXI. (1925). p.103.

biotite. It, therefore, seems that the biotite is produced by a combination of chlorite and sericite. Assuming that the chlorite has a composition represented by the formula given on p , and that the sericite is of a phengitic character, such changes can be represented as follows:

$$3(5(MgFe)O.2Al_2O_3.3SiO_2.5H_2O) + 3(K_2O.(MgFe)O.2Al_2O_3.7SiO_2.2H_2O) + 4Fe_3O_4 + 3K_2O$$
(chlorite) (sericite) (magnetite)

$$= 6(K_2O.2H_2O.5(MgFe)O.2Al_2O_3.5SiO_2) + 9H_2O + 2O_2$$
(biotite)

It is possible that some of the manganese carbonate enters into the reaction in place of some of the magnetite. Tilley[1] gives the following reaction:

$$K_2H_4Al_6Si_6O_{24} + 2.H_4Mg_3Si_2O_9 = \begin{pmatrix} K_2H_4Al_6Si_6O_{24} \\ 3Mg_2SiO_4 \end{pmatrix} + SiO_2 + 4H_2O$$
(white mica) (chlorite) (biotite)

When all the sericite has been used up, the production of biotite from chlorite alone may be represented as follows:

$$5(MgFe)O\ 2Al_2O_3\ 3.SiO_2 5H_2O + 2SiO_2 + K_2O = K_2O 5(MgFe)O.2Al_2O_3 5SiO_2 2H_2O + 3H_2O$$
(chlorite) (silica) (biotite)

Evidence for the last reaction seems to be forthcoming in the deficiency of sericite which many of the normal mudstones show. As would be expected all these reactions involve dehydration.

In the first reaction represented above, it will be noted that considerable amounts of magnetite are required to satisfy the reaction. The normal mudstones contain considerable amounts of magnetite. In these rocks, however, all the minerals - chlorite, sericite, biotite, spessartite, and dialogite - are deficient in ferric oxide, and so practically all the ferric iron represented in the analyses will represent the magnetite content of the rock. It will, therefore, be seen, by comparing analyses III and IV with I and II that the biotite rocks contain less magnetite than their corresponding chlorite-sericite originals. It is, therefore, reasonable to believe that this relative deficiency is represented by the amount taking part in the biotite-forming reaction, and which is thereby reduced to the ferrous state.

A further progressive stage in this metamorphism is represented by

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[1] "Contact Metamorphism in the Coombie Area of the Perthshire Highlands." Q.J.G.S. LXXX. (1924). p.60.

the garnet-quartz rock (4, pp. 74-78) this rock is composed essentially of minute garnets, with subordinate quartz and minor chlorite. It will be seen from analyses V and Va that the bulk analysis of this rock is approximately the same as those of the chlorite-sericite mudstone and the biotite-bearing mudstone. The only variations: the small amount of iron; a marked deficiency in ferric (which is consequent on its transformation to the ferrous state during the formation of garnet); and a somewhat larger amount of CaO. However these are not major discrepancies, and one is justified in regarding the rock as resulting from mineral transformations without any addition of material from extraneous sources.

In normal regional metamorphism the oncoming of garnet marks a further advanced stage in metamorphism, and garnet is found as the next mineral appearing after biotite. This is the case in the Southern Highlands (Barrow, Tilley) and in the Trondhjem region of Southern Norway (Goldschmidt) In this case, also, it clearly represents a stage beyond the formation of biotite. Since the garnet forms most of the rock, and quartz makes up most the remainder, the analysis Va, if excess SiO_2 be eliminated, represents fairly accurately the composition of the garnet. It will be noted that it is still very rich in MnO, but compared with the colourless garnets of the chlorite-sericite zone it is probably much richer in FeO and CaO than they were. Goldschmidt, in the Stavanger area, noted that when garnets were formed accompanying both low grade and high grade metamorphism, the high grade garnets show a decreasing content of manganese with a corresponding increasing content of iron, the garnets tending to approach the normal almandine type of garnet, characteristic of ordinary regional metamorphism.

The small crystal size of the garnets and the presence of small amounts of interstitial chlorite indicates that this garnet zone indicates a much lower grade of metamorphism than the normal garnet zone of regional metamorphism. This would be due to the still very high percentage of spessartite molecule present in the garnet formed, a factor which as indicated before promotes garnet-formation. The very small size of the garnets formed in these rocks is probably due to the relative ease of formation of the garnets when manganese is present. Many centres of

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[1] Videnskr. Skr. 1920. (No.10). 1921. p.69.

crystallization would readily be initiated, and the garnet material would thereby used up before the individuals reached any marked size. The occurrence of very small garnets which contain very notable manganese percentages is recorded by Coulson[1], H. Williams[2], Fermer[3], F.C. Phillips[4] and Renard[5].

The chlorite accompanying these garnets is very pale, not visibly pleochroic, and has a very low birefringence. It indicates a magnesium-rich penninite type of chlorite. This indicates that in the formation of garnets from chloritic minerals, iron is taken up by the garnets far more readily than is magnesium, and that while, with increasing metamorphism, garnets are enriched in iron, any residual chlorite is enriched in magnesium. Tilley[6] states: "in these cases (garnet-chlorite associations) the chlorites are all much richer in magnesia than the garnets. Actual exchange of magnesia for ferrous oxide, alumina being unchanged, is suggested".

The original magnetite of the rock is practically entirely destroyed (note the very low ferric iron content) as is also the dialogite, both these minerals entering into combination with the alumino-silicates to form the garnet. Neglecting the intermediate stage of the formation of biotite the reaction can be represented as follows:

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[1] Coulson, A.L.: "Magnetite and Garnet Rocks from the Moraines, Cape Denison, Adelie Land", Austr. Ant. Exped. 1911-4. Sci. Rep. Ser.A. Vol.III.
p.289. Garnets are numerous but their size is small, some of the grains, especially the smaller ones showing anomalous double refraction". Does the latter merely mean that the individuals are so small that they do not extend through the thickness of the section? "Garnets are numerous and form one-fifth of the rock, but the average size of the grains is only 0.06 mm. The chemical analysis shows that the rock contains 8.23 per cent of the MnO, and it is probable that it is contained in the garnet".

[2] loc. cit. pp.360-1. fig. 2B.

[3] Fermor, L.L. "The Manganese ore Deposits of India". Mem. Geol. Surv. India. Vol.XXXVII. Pt.II. plate 11. fig.1- . "very fine grained gondite".

[4] Geol. Mag. LXV. (1928). p.550 - minute spessartite garnets in chlorite phyllites.

[5] Renard, A. ("Sur la structure et la compesition minéralogique du Coticule et sur ses Rapports le Phyllade Oligistifere"; Mem. Cour. et Mem. de Savants etrangers l'Acadamie Roy. Belg. Vol.XLI. No.2. (1878.) p.22.) records spessartite garnets, more than 100,000 to the cubic millemetre, in the novaculites of the Cambrian of the Ardennes.

[6] Min. Mag. XXI. (1926) p.44.

$$2Al_2O_3.5(MgFe)O.3SiO_2.5H_2O + K_2O(MgFe)O.2Al_2O_3 7SiO_2.2H_2O + 3MnCO_3 + Fe_3O_4 + 2SiO_2$$
(chlorite) (sericite) (dialogite) (magnetite)

$$= 4[3(FeMnMg)O.Al_2O_3.3SiO_2] + 7H_2O + K_2O + 3CO_2 + O$$
garnet

or, allowing dor the formation of penninite:

$$2[3FeO.2MgO.2Al_2O_3.3SiO_2.3SiO_2 5H_2O] + 2[K_2O.(MgFe)O.2Al_2O_3.7SiO_2 2H_2O] +$$
(chlorite) (sericite)

$$9\ MnCO_3 + 2\ Fe_3O_4 + 6SiO_2$$
(dialogite)

$$= 8[3(MnMgFe)O.Al_2O_3.3SiO_2] + H_2O.3MgO.2SiO_2 + 13H_2O + K_2O + O_2 + 9\ CO_2$$
(garnet) penninite)

These reactions again involve dehydration and in addition, decarbonation.

Thus the three rock types-quartz-chlorite-sericite-spessartite mudstone, quartz-chlorite, biotite, spessartite mudstone, and the quartz-garnet rock represent three stages of metamorphism of the same original rock type. They have similar bulk chemical compesition and so form an isochemical series.

The fourth type - the calcite-muscovite rocks (Ø.pp.76-82), present a rather different problem. Consideration of the chemical analyses (VI and VII) show that there are marked discrepancies in their analyses as compared with those of the preceding types, and consequently they cannot be regarded as isochemical with the latter. The chief points of difference are: the lower silica content; the higher alumina content; the much lower manganese content; the somewhat higher magnesia content; and the much higher CaO content. Therefore the rock, as it stands cannot be regarded, as a metamorphic derivative of the normal mudstone by mere mineralogical transformation.

Mineralogically the rock differs from the normal rock in possessing scalenohedral crystals of calcite and well developed muscovite. The calcite was isolated by hand picking under a binocular microscope after rough crushing. The material so obtained was analysed with the following results:

	(I)	(II)
SiO_2	16.31	
Al_2O_3	2.56	
Fe_2O_3	1.77	1.97 (FeO)
MnO	3.34	4.15
CaO	41.10	51.00
CO_2	34.54	42.88
	99.62	100.00

(I) is the analysis of the separated material, and (II) is the computed analysis of the calcite. It is a manganocalcite containing 4.15 p.c. of MnO.

In order to find out whether the matrices of the rocks bore any relationship to the normal mudstone or to themselves, their analyses were computed from the bulk analyses of the rocks by subtracting the calcite as indicated by the CO_2 content. The following results were obtained:

	VIb	VIIb
SiO_2	39.52	42.94
Al_2O_3	28.26	21.00
Fe_2O_3	14.63	2.10
FeO		11.84
MnO	1.86	5.08
MgO	7.99	3.07
CaO	1.92	4.63
Na_2O	2.15	1.02
K_2O		3.85
H_2O	3.67	4.24
P_2O_5	N.D.	0.15
S	N.D.	0.08
	100.00	100.00

From these it is seen that the matrices of these rocks also bear no relationship to the ordinary mudstone. Therefore the calcite-muscovite bearing rocks must be regarded as separate metamorphic derivations of the bluestone mudstone. They differ from the normal rocks mainly in their greater calcite content, and, to a lesser degree a greater magnesia content, the increase in these constituents being accompanied by a lesser manganese content. There is also an increase in alumina and iron at the expense of silica.

It is not easy to see how the increase in calcium came about. There is no evidence whatsoever that it has been brought about by bodily introduction from extraneous sources, and no basic (or acid) igneous rocks are recorded anywhere in the immediate locality. Veining is not common and the calcite rocks themselves are practically unaffected by veining. What veins do occur in the locality are ordinary quartz veins, with little or no calcite. On the other hand there is some evidence, not conclusive, that t these differences were original. The maximum developments of calcite

scalenohedra are aligned along bedding planes and there is never transgression of these calcite layers across the bedding of the rocks. In addition they have clearly grown "in situ", since the crystal, under the microscope, show the small scale bedding of the rock passing through as differences in the concentrations of the argillaceous inclusions. Again, there was an original difference in this material as compared with the normal muds, reflected by the greater alumina and iron and lesser silica content, thus indicating of course a greater proportion of clayey materials to quartz than was usually the case. However, even assuming that the differences were original, it is not easy to see why calcium (and magnesium) should be deposited, in this one locality, at the expense of manganese. There is evidence that this locality lies approximately near the centre of the original basin of deposition. Any calcium present in the waters would tend to be concentrated near the centre, owing to the fact that it is not as readily precipitated as manganese and therefore would tend to be carried further by the moving waters and would finally be precipitated as carbonate near the centre of the area of deposition.

Whatever the real cause of the increased calcium content in these rocks the fact remains that it is largely responsible for the peculiar mineralogical character displayed by them.

The large scale recrystallization of muscovite in these rocks suggests that the aluminous minerals were largely of a sericitic composition. The fact that the chlorite in the rock is pale green and only feebly pleochroic, suggests that it is a magnesium-rich variety, and that the muscovite is a phengitic type rich in ferrous iron. These rocks pass into the garnet-quartz type of rock and this indicates that the grade of metamorphism represented by the recrystallization of the muscovite and the formation of calcite is approximately equivalent to the biotite grade of the same locality. The reason why biotite was not formed is probably because the original mudstone was so poor in the ordinary chloritic materials. During the crystallization of the muscovite there was probably transference of FeO from the chlorite to the mica, leaving a relatively magnesia-rich chlorite. The calcite, of course, must have recrystallized from the original finely divided calcium carbonate, tending slightly to post-date the formation of the muscovite[1].

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[1] See p. 79

Thus two metamorphic sequences seem to be represented in this locality:

(1) the normal sequence: chlorite-sericite → biotite → garnet.

(2) a peculiar variation depending on variations in composition:
chlorite-sericite → muscovite-calcite → garnet.

The reason for the localization of these peculiar metamorphic types just in this small localized area is to be found in the local tectonics. The small area which embraces all these types lies in the apex of a pitching monoclimal syncline on the N.W. side of Moelfre. The pitch is approximately westward and the south limb of the fold drips approximately northward. The apex of this fold would be a region of increased pressure, which would be responsible for the mineralogical changes demonstrated. Apart from the mineralogical changes, the localized increase in pressure is clearly shown in the minor crumpling exhibited especially in the garnet quartz rock and shown in the photographs of Pl. 4 figs. 1 & 2

(The garnet-quartz rock was also recorded in the Cwm Mawr locality, where also minor crumpling indicated increased pressure.)

TABLE.

Chemical Analyses of the "Bluestones" and their Metamorphic Derivatives.

	I	II	III	IV	V	VI	VII
SiO_2	40.96	42.57	41.81	46.90	54.39	32.13	40.71
Al_2O_3	12.84	13.08	12.28	14.86	15.70	22.97	19.90
Fe_2O_3	3.23	4.89	2.72	2.23	0.49	13.59 chiefly FeO	1.99
FeO	6.49	5.30	6.18	7.09	6.12		11.34
MnO	13.59	12.23	12.89	8.57	12.44	2.25	5.05
MgO	2.44	1.81	1.92	2.00	1.74	6.50	2.91
CaO	2.67	2.72	4.48	3.35	6.69	11.04	7.26
Na_2O	1.14	1.57	1.76	2.01	N.D.	1.75	0.97
K_2O	3.60	3.92	4.57	4.46	N.D.		3.65
P_2O_5	0.23	0.20	0.26	0.25	0.18	N.D.	0.14
H_2O-	0.05	0.06	0.05	0.06	0.06	0.05	0.04
H_2O+	2.43	1.84	3.08	2.95	0.12	10.59	3.88
CO_2	10.14	9.37	7.74	4.87	1.07		2.41
S	0.10	0.16	0.18	0.14	0.07	N.D.	0.08
	99.91	99.72	99.92	99.74	99.57	100.87	100.33
	Ia	IIa	IIIa	IVa	Va	VIa	VIIa
SiO_2	49.80	51.51	50.82	55.16	55.98	36.32	45.59
Al_2O_3	15.62	15.82	14.92	17.48	16.01	25.96	22.29
Fe_2O_3	3.92	5.92	3.30	2.63	0.50	15.36 chiefly FeO	2.22
FeO	7.89	6.42	7.52	8.34	6.24		12 71
MnO	16.53	14.82	15.65	10.09	12.68	2.54	5.79
MgO	2.97	2.19	2.34	2.36	1.77	7.35	3.26
CaO	3.25	3.28	5.45	3.94	6.82	12.47	8.14
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

I: quartz-chlorite-sericite-spessartite-dialogite mudstone; St.John's Church, Barmouth.

II: quartz-chlorite-sericite-spessartite-dialogite mudstone; Egryn Mines, 3½ ml. N. of Barmouth.

III: quartz-chlorite-biotite-spessartite-dialogite mudstone; Hendre Mines N.of Moelfre.

IV: quartz-biotite-chlorite-spessartite-dialogite mudstone; Hendre Mines N. of Moelfre.

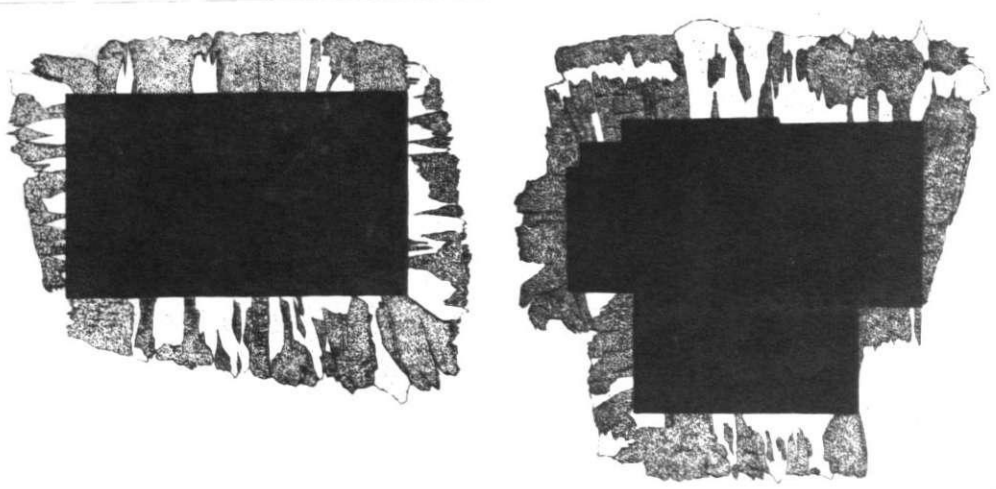
V: quartz-garnet rock; Hendre Mines, N. of Moelfre.

VI: calcite-muscovite-chlorite rock; Hendre Mines, N. of Moelfre.

VII: muscovite-chlorite-calcite rock; Hendre Mines, N. of Moelfre.

The "a" analyses were calculated by subtracting the constituents - alkalies. P_2O_5, H_2O, CO_2 and S, i.e. those lost on metamorphism, from the bulk analyses.

THE DEVELOPMENT OF IRON PYRITES IN THE GRITS AND MUDSTONES.



A B.

Fig. 14 Pyrite crystals from the "Bluestone Grit"; Cwm-yr-Afon Mines.

The pyrite crystals are surrounded on all sides by a fibrous intergrowth of bright green chlorite and chalcedonic silica, the interlocking fibres being developed with the long axes perpendicular to the crystal faces.

A. Simple crystals of pyrite.

B. Compound crystal of pyrite.

The Development of Iron Pyrites in the Grits and Mudstones.

Pyrite occurs associated with rocks of practically all grades. It is, on the whole, least abundant in the grits, but even in these it becomes locally fairly abundant. In the mudstone rocks, e.g. the "bluestone", it occurs at various horizons, each band being invariably very impersistent laterally. Immediately below the ore horizon, however, a very persistent band of green mudstone containing abundant pyrite crystals is to be observed which indicates that iron sulphide was at that time being laid down contemporaneously over the whole area. Although its general characters are the same, this band varies slightly in detail when traced laterally, and these differences are noted in the following descriptions. In addition examples of pyrite bearing mudstones from the "bluestone" are described, and the pyrite crystals from the pyritiferous "Bluestone Grit" from the Cwm-yr-Afon Mines (described on pp.32-3).

I. Petrographic Characters.

The pyrite crystals in the "Bluestone Grit" from the Cwm-yr-Afon Mines (see pp.32-3) are beautifully developed. They occur as well-formed cubes, often with unequal development along the axes, so that cross sections of the crystals are rectangular; triangular outlines are obtained when the section is cut diagonally to all three axes. Usually simple crystals are developed, as in Fig. 14A but sometimes compound crystals, consisting of a cluster of interfering individuals, growing along approximately parallel axes occur, as in Fig. 14B In size the crystals vary from 0.6 mm. to the dimensions of the two figured crystals, which are 1.52 mm. X 0.88 mm. and 1.55 mm. X 1.31 mm. respectively.

The crystals are surrounded by a zone of fibrously intergrown chlorite and chalcedonic silica. This zone varies in thickness from about one-fifth to one-quarter of the depth of the crystal. The chlorite and the silica fibres interlock perfectly and they are orientated with their length at right angles to the crystal faces which they adjoin. Sometimes chlorite is developed along one or more faces to the almost complete exclusion of chalcedonic silica, but sometimes silica makes up as much as two-thirds of the material of the zone. Never, however, does silica alone occur. When it occurs, the silica tends to take up the interior portion of the zone, adjoining the crystal, and the chlorite is

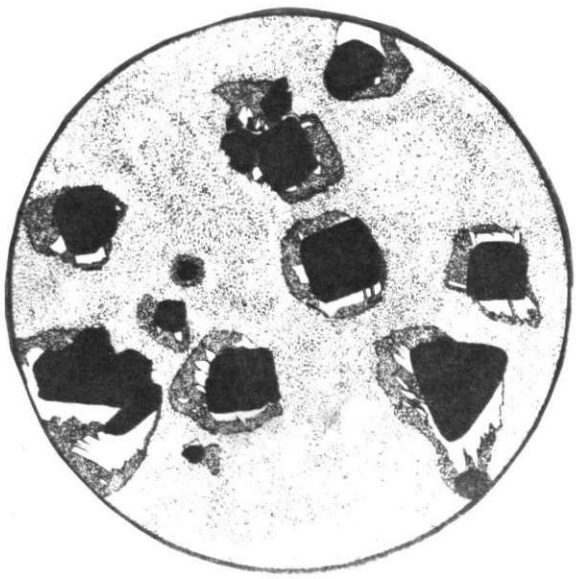


Fig. 15 Pyritiferous rock below the ore: Cell Fechan, near Barmouth.

Pyrite crystals with surrounding chlorite-silica zones embedded in a very fine-grained mudstone matrix. The silica is confined to the inner portion of the zone.
Magnification x 13 diams.

more or less confined to the outer portions. The zones are remarkably free from inclusions of the normal rock matrix, and the junction of the zone with this is well defined. The junction between chlorite and matrix is well seen in ordinary light, while that between chalcedony and the matrix stands out more clearly with crossed nicols.

The silica is clear and colourless and contains very minute opaque inclusions. The fibrous character is best seen with polarized light.

The chlorite is green and has a well marked pleochroism, from yellowish-green to emerald green, the greatest absorption being at right angles to the length of the fibre, and parallel to the cleavage which is not well-marked and approximately at right angles to the length of the fibre. The refractive ibdex is considerably higher than that of the chalcedonic silica, and with polarized light gives ultra-blue and purple interference colours. No figure is obtainable.

A typical example of the pyritiferous horizon below the ore at Cell-fechan, $\frac{1}{4}$ mile N.W. of Barmouth has the following characters. Macroscopically it is a green or grey-green striped rock, with a "bluestone" lithology. The mudstone is of uniformly fine grain and slightly cleaved; the striping is in regular bands 0.5 mm. to 2 mm. wide. Pyrite crystals up to about 1 mm. in size, occur in individual layers coinciding with the bedding. The amount of pyrite developed in any layer varies from occasional crystals, through regularly distributed, closely-packed crystals forming a layer one crystal thick, to much thicker layers up to one quarter of an inch. Within such layers as the latter, the concentration of crystals varies laterally from relatively sparse to closely crowded together. The mudstone itself shows a distinct manganiferous weathering.

Under the microscope (sections being cut parallel to the bedding) the rock is seen to be composed of frequent pyrite crystals set in a very fine-grained matrix (Fig. 15). The pyrite crystals do not present perfect crystals. For the most part they consist of irregular cubes, sometimes with curved faces and rounded coigns, and in a less degree of irregular masses. In size they vary from 1.0 mm. to 1.4 mm. Each is surrounded by a zone in which fibrously intergrown chlorite and chalcedony are developed to the exclusion of matrix material. The chlorite is identical with that described above. The silica and chlorite fibres again show parallel intergrowth and are developed at right angles or approximately at right angles to the crystal faces. The silica is again confined to the inner

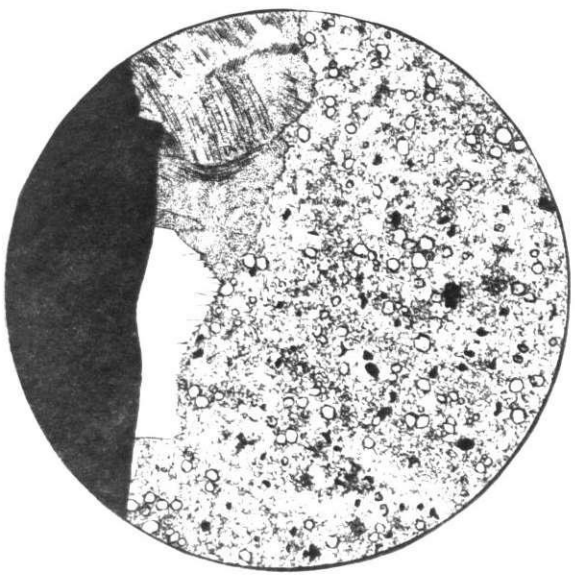


Fig. 16. Pyritiferous mudstone below ore; Cell Fechan, near Barmouth.

Zone of fibrous chlorite and silica surrounding pyrite, the whole set in a matrix of fine-grained chlorite, quartz and dialogite, throughout which is scattered numerous small colourless spessartite garnets. Magnification x 125 diams.

margin of the zone and the chlorite to the outer part. Occasionally silica is absent, in which case the fibrous chlorite is developed uniformly throughout. Frequently some faces have no zonal development, but no crystal was observed in which it was entirely absent, each having at least two sides (in section) which possess such a zone. The junction of the chlorite zone with the rock matrix is abrupt and clearly defined. The total area (in section) of the zonal material is, on the average, equal to at least one half that of the crystal around which it is developed.

The matrix is extremely fine-grained - approximately 0.015 mm. grade. It consists of an intimate intergrowth of manganese carbonate (dialogite), chlorite and spessartite, with small amounts of silica and subordinate iron ores - magnetite and pyrite. Owing to the small dimensions of the grains and their overlapping in section, it is difficult to calculate the relative proportions. Approximately, manganese carbonate appears to make up 40-50 p.c. of the total. The carbonate is colourless and clear. It has a high double refraction (approximately 0.20), and a refractive index which varies from approximately equal to that of the chlorite to quite well above it. No good crystal shapes are seen, due partly to mutual interference and partly to the interstitial character of the carbonate, but very occasional grains under oil immersion suggest rhombohedra.

The chlorite is identical with that described in the grits and mudstones: bright green, with a fairly well-marked pleochroism; fibrous and tabular in character, tabular crystals having "pseudo-hexagonal" terminations; low birefringence and refractive index higher than that of the silica.

The silica is largely interstitial and has the chalcedonic appearance noted previously. Under low powers, however, some grains appear to have a detrital character. It is sporadic and forms only a small proportion of the rock.

The spessartite crystals have the same characters as described in the matrix of the grits and in the mudstones. In size they vary from 0.007 mm. to 0.014 mm., averaging 0.010 mm. They have a high refractive index and tend to stand out fairly well (Fig. 16). They make up about 5 p.c. of the rock matrix. In addition the minute reddish-brown garnets described in the grits again occur.

The iron ores form a small proportion of the rock: they consist of black opaque bodies of irregular shape 0.015 mm.-0.025 mm., which are probably detrital magnetite, and small black fragments, approximating to cube

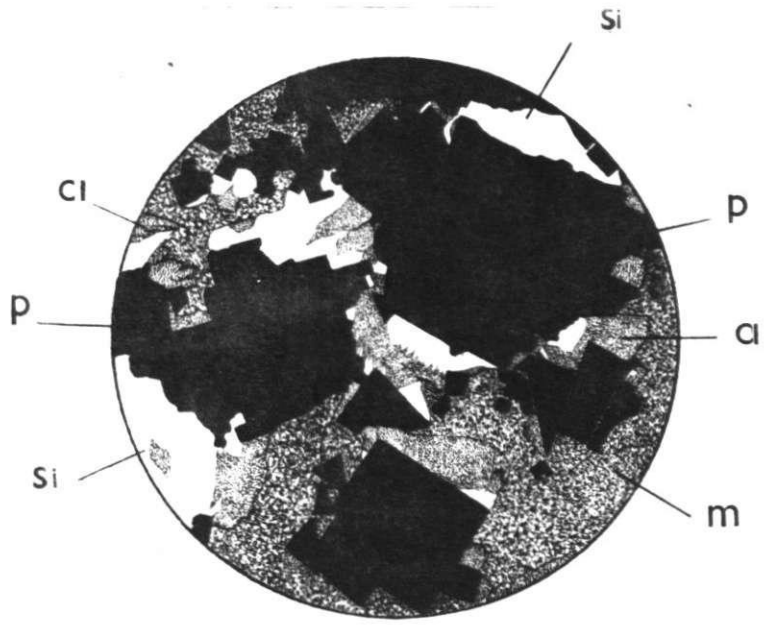


Fig. 17. Pyritiferous layer below the ore: East side of Llyn Dywarchen.

The pyrite occurs in isolated and compound crystals with surrounding zones of chlorite and chalcedonic silica. Note the tendency for the individuals of the same compound crystal to have the same crystallographic orientation.

P: pyrite; Cl: chlorite; Si: silica;
m: rock matrix.

Magnification × 13 diams.

outlines, which are authigenic magnetite (and/or pyrite).

On the east side of Llyn Dywarchen, the pyrite band below the ore is a fine-grained, green mudstone containing large developments of pyrite crystals. The pyrite occurs throughout at a thickness of three-quarters of an inch of rock. In the lower portion of this band it is concentrated along two narrow bands 1/16th-1/12 inch thick, separated by 3/16 inch of pyrite-free green mudstone; 1/8 th inch of pyrite-free mudstone again follows and finally the upper part of the band developes pyrite throughout. The concentration of the pyrite is along planes coincident with the bedding. In size the crystals vary from 1/50-1/40th inch to 1/12-1/10th inch. The latter tend to be confined to the thicker layer in the upper portion of the pyrite, while the former largely make up the layers in the lower portion. When a crystal is removed it leaves behind a dark green glossy cast, due to the chloritic material surrounding it.

The microscopic characters (in a section cut approximately parallel to the bedding) are as follows. Abundant pyrite, surrounded by chlorite-chalcedony zones in a similar manner to those already described, are set in a very fine grained matrix consisting of very small detrital grains of quartz with interstitial chlorite and much authigenous magnetite.

The pyrite is so abundant that compound crystals have developed largely to the exclusion of simple isolated crystals (Fig. 17). The compound crystals show, on their margins, good euhedral boundaries, with the typical sharp right angles, rectangular and triangular outlines. The crystals are orientated haphazardly, but in local clusters the individual crystals seem to possess the same orientation. Fig. 17 (west) shows a good example of a cluster of similarly orientated crystals, cut normal to one of the axes, while in Fig. 18A such a cluster is cut oblique to all axes. The large crystals (up to 3.5 mm.) are almost invariably compound crystals, while the isolated euhedra are much smaller in size - 0.15 mm.-0.25 mm. Abnormal development along one or two of the axes is not uncommon, very elongate rectangular crystals occasionally resulting.

The pyrite is completely or incompletely surrounded by zones of secondary chlorite and chalcedony. Owing to mutual interference and proximity of crystals and crystal clusters, the arrangement and nature of these zones is subject to local modification, some sides of the crystal or crystal-cluster possessing an abnormally wide zone, while on another it may be entirely absent (Fig. 17). The same generalizations as have been already

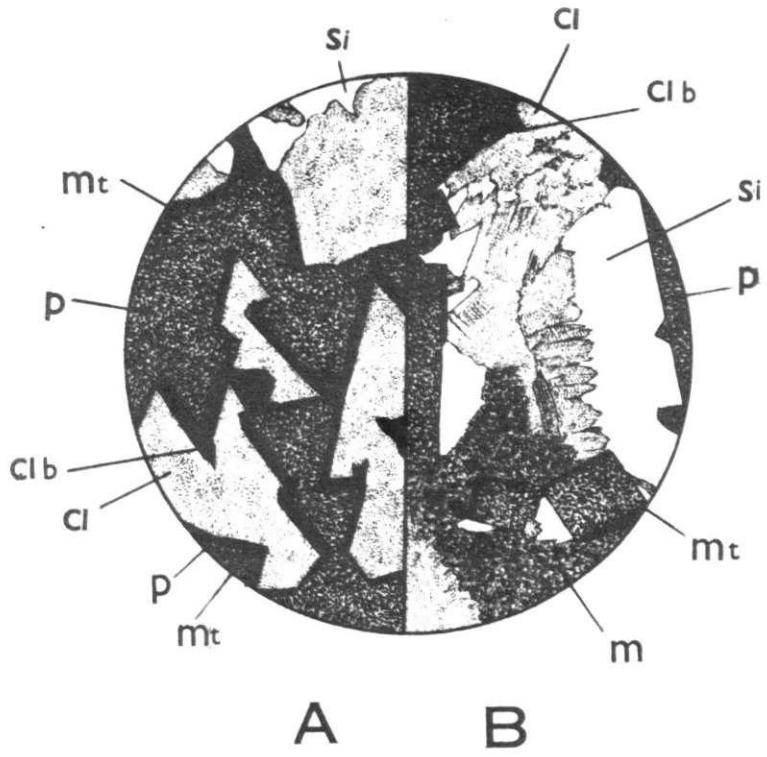


Fig. 18. Pyritiferous band below the ore; East side of Llyn Dywarchen

A. Shows the magnetite zone surrounding the pyrite crystals, associated with green chlorite. Note also the occurrence of the brown chlorite between the magnetite and the green chlorite, and the parallel orientation of the individuals of a cluster of crystals.

B. The magnetite zone is absent when silica is present in the surrounding zone. The matrix contains abundant small authigenic crystals of magnetite.

Mt: magnetite; p: pyrite; Cl: green chlorite; Cl.b: brown chlorite; Si: silica; M: magnetite bearing matrix.

The opaque minerals are represented in reflected light and the transparent minerals in ordinary light. Magnification × 40 diams.

noted hold: fibrous intergrowth of chlorite and silica; fibres orientated at right angles to the crystal faces; invariable occurrence of chlorite, silica being more sporadic; when silica does occur it tends to be confined to interior portion of the zone. Both chlorite and silica have the same optical properties as already described.

This section, however, shows an interesting modification of the zonal development. Most of the pyrite crystals show, on some of their margins at least, a regular zonal development of an opaque material, black in reflected light, and consequently standing out clearly from the pyrite itself when so examined (Fig. 18). It is regarded as magnetite, from its similarity to the undoubted magnetite in the rock matrix, and this diagnosis is confirmed by the action of a magnet on material scraped from a cast of a pyrite crystal. The thickness of this magnetite zone varies slightly along different faces of the same, and in different crystals, but along any given crystal-face the zone is remarkably uniform in behaviour, being of uniform thickness and adhering tightly to the face of the crystal. In thickness these magnetite zones vary from 0.012 mm. to 0.06 mm. They are almost invariably present when chlorite is developed on the internal part of the zone to the exclusion of chalcedony (Fig. 18A). When the chalcedonic silica is developed it occupies as usual the internal part of the chlorite-silica zone, and, in this case, though not invariably, there is a marked tendency for the magnetite zone to be absent from that face of the crystal (Fig. 18B). The following generalizations, therefore, seem to be justified: (a) when chlorite, to the exclusion of silica forms the zone surrounding the pyrite, a thin magnetite zone is developed between the chlorite and the pyrite itself; (b) when silica is present as well as chlorite, the silica occupying the internal part of the zone, no magnetite zone is developed between the silica and the pyrite.

When this magnetite zone is developed, surrounded on the external side by green chlorite, it is not uncommon to find a small irregularly developed zone of yellowish-brown chlorite developed between the magnetite zone and the green chlorite. This brown chlorite has a higher refractive index and a higher double refraction than the green chlorite. It appears to be a cronstedtite type of chlorite, or at any rate, to be a ferric iron-rich chlorite. This brown chlorite is never observed in any other position but adjacent and external to the magnetite

zone.

The matrix consists in the main of small irregular fragments of quartz (0.02 mm. to 0.025 mm.) with abundant interstitial material consisting chiefly of green chlorite similar to that already described from these matrices (of a similar grain size). The chlorite is developed in the typical lath-shaped forms in a more or less parallel manner, approximately in line with the bedding. The ratio of quartz to chlorite varies locally from 3:1 to 1:3. Throughout are developed small quantities (about 5 p.c.) of dialogite. This occurs in small globular masses, 0.03 mm. to 0.06 mm. in size and it has the usual carbonate characteristics. It has a fairly regular distribution throughout the section.

Throughout the matrix are developed large quantities of authigenic magnetite. In quantity they make up 5-25 p.c., their density varying somewhat in different parts. They possess euhedral outlines, showing sections of octahedra. Their diagnosis was confirmed by separation by means of an electro-magnet from the rock powder, the magnetite crystals so obtained, showing octahedral forms.

The minute spessartite garnet, so common in these rocks, is almost entirely absent, rare isolated crystals only occurring.

The pyritiferous layer below ore on the east slope of Diphwys is a dark greyish-green mudstone with abundant pyrite crystals concentrated along lines of bedding, the individual layers being upwards of $\frac{1}{8}$th inch thick. The thickness of the pyrite-bearing mudstone is about $1\frac{1}{4}$ inches. The pyrite crystals vary from about $\frac{1}{32}$nd inch to $\frac{1}{8}$ th inch, an average being about $\frac{1}{16}$th inch. The silica of the zones surrounding the pyrite can be seen in hand specimen; the chlorite is more obscure but can be seen as the glossy dark green material left behind in the cast after removal of a crystal. Along one bedding layer the pyrite is seen to be accompanied by a brown carbonate material with incipient rhombohedral cleavage. Quantitstive chemical tests confirmed the diagnosis of this mineral as siderite.

Microscopically, the rock consists of simple and compound crystals of pyrite set in a fine-grained magnetitiferous matrix. In size the pyrite crystals themselves are similar to those from Llyn Dywarchen, and like them they have well developed zones of secondary chlorite, silica and magnetite surrounding them. The same generaliza-

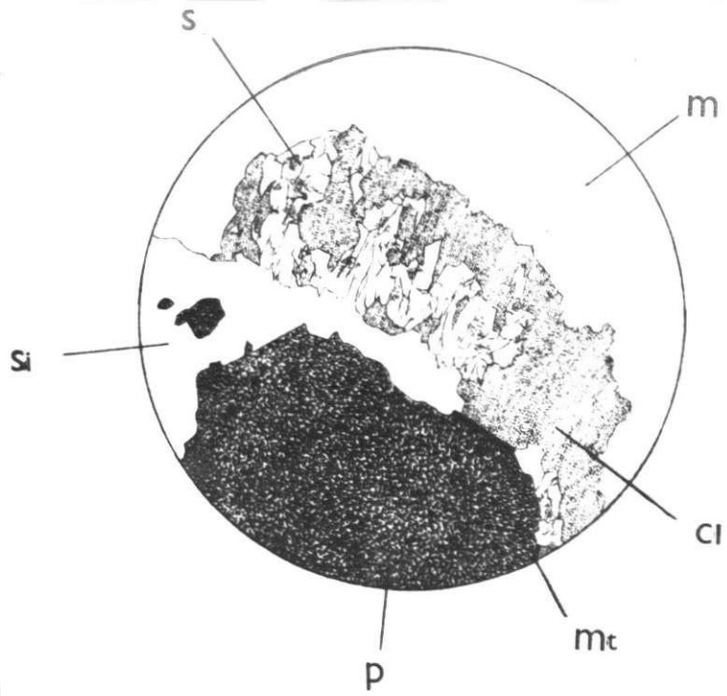


Fig. 19 Pyritiferous layer below the ore; East side of Diphwys.

When siderite occurs in the zones surrounding the pyrite and silica is also present, it takes up a position between the chlorite and the silica. Note the absence of the magnetite zone when silica is present.

S: siderite; Cl: chlorite; Si: silica;
P: pyrite; Mt: magnetite; M: rock matrix.

Magnification x 40 diams.

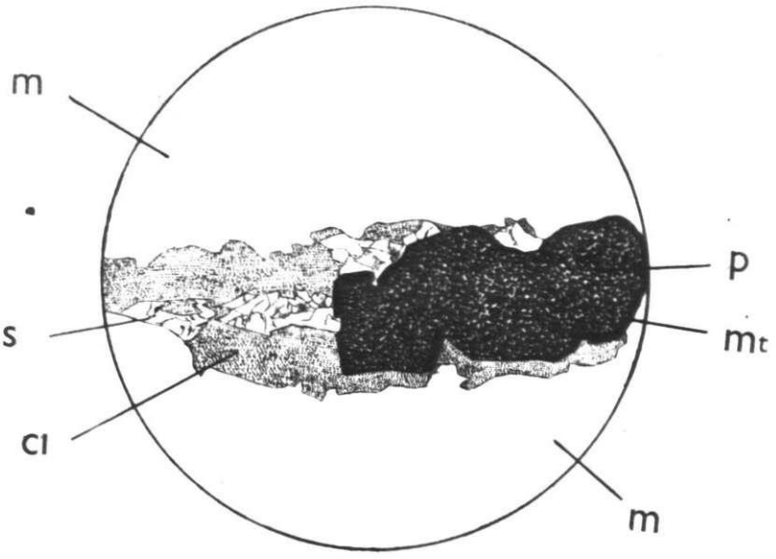


Fig. 20. Pyrite layer below the ore; East slope of Diphwys.

In this case siderite is associated with green chlorite in the zone surrounding the pyrite, silica being absent. The siderite occupies the internal part of the zone. Note the presence of the magnetite zone in the absence of silica.

S: siderite; Cl: chlorite; Mt: magnetite;
P: pyrite; M: rock matrix.

Magnification x 40 diams.

tions with regard to these zones can again be made. The brown chlorite was practically absent, a few small scattered developments being noticed adjoining the magnetite band as before

The presence of the siderite referred to above, further complicates the story of the zonal developments surrounding the pyrite crystals, for this too has been developed as a constituent of the zone. In section it is colourless in places showing rhombohedral cleavage. It has a very marked tendency to be intergrown fibrously with the chlorite, and then its rhombohedral cleavage is not so well marked. It has a refractive index varying from slightly below that of the chlorite to somewhat above, and its double refraction is approximately 0.20. It possesses an uniaxial figure. Occasionally it shows decomposition along cracks and lines of cleavage, leaving behind a reddish-brown material referred to limonite or haematite.

The position of the siderite in the zonal sequence is more obscure than that of the other minerals. It occurs when silica is absent, associated with the chlorite, on the inner part of the zone adjacent to the crystals. Its outer margins are fibrously intergrown with the fibres of chlorite, and both are aligned, as usual, normal to the adjoining pyrite walls. The magnetite zone is sometimes developed, when it takes the position between the siderite and the pyrite. The siderite occurs when both chlorite and silica are developed, and it then tends to occupy a position between them, all three possessing a fibrous character, with the fibres orientated normal to the walls of the crystal. In this case, as usual, the magnetite zone is absent. Sometimes the siderite occurs completely enclosed by chlorite, though still in the inner portion of the zone, but it never appears completely enclosed by silica.

The matrix is composed of abundant minute crystals of a black, opaque mineral, 0.025 mm.-0.035, average 0.03 mm., set in a transparent material much fines in grain size and composed essentially of an intimate admixture of green chlorite, quartzose material and dialogite. The opaque minerals are euhedral and present rectangular and trapezuim outlines in section; they are dark blue-black in reflected light. Some of the rock specimen was powdered, and from this powder the opaque mineral was easily separated by magnetic means. The material was mounted and examined; it consists of minute octahedra of magnetite. This magnetite sometimes forms as much as 50 p.c. by volume of the rock in this section and is undoubtedly authigenous. The presence of the magnetite zone around the pyrite crystals in a rock, the matrix of which contains abundant authigenous magnetite, is noteworthy.

The transparent minerals consist chiefly (about 50-60 p.c.) of green chlorite of the same type as that described already from these rocks. The quartzose material appears to be partly secondary, i.e. more or less contemporaneous with the formation of the chlorite, and partly detrital. The former is water clear and interstitial and the latter has a fragmentary appearance and contains abundant very minute inclusions. The carbonate is again interstitial and colourless. It is not abundant and is regarded as being dialogite, as manganese is undoubtedly present as witnessed by the manganiferous weathering of the rock surface.

Scattered throughout but not frequent, are the minute (0.008 mm.-0.01 mm.) six-sided euhedral crystals of colourless spessartite identical with those already described.

Under the oil immersion objective very occasional very small lath-shaped crystals of brown tourmaline (0.03 mm.-0.04 mm.) are observed. These are elongate prismatic crystals with length to breadth varying from 6:1 to 3:1, and they nearly all possess perfect rhombohedral terminations. They are pleochroic from pale yellow-brown to greenish-blue, with maximum absorption at right angles to the length of the crystal. They contain very minute inclusions of what appears to be opaque matter. From their euhedral character they are regarded as being authigenous in character.

A portion of the pyritiferous band at base of ore (Lower Hendre mines, N.W. slope of Moelfre) is made of two pyritiferous layers, each approximately $\frac{1}{4}$ inch thick, separated by a more or less non-pyritiferous layer $\frac{1}{4}$ inch thick. The fine-grained rock matrix is itself composed of three bedding layers. Two layers of deep olive green, corresponding to the pyritiferous layers, are separated by a layer of much paler green material more or less identical with the non-pyritiferous portion.

Under the microscope the pyrite is more or less similar to that described in other sections of the pyrite band below the ore. It consists of isolated euhedra and compound crystals of irregular shapes, imperfectly surrounded by zones of secondary materials: chalcedonic silica, lesser chlorite and subordinate siderite and magnetite. All are developed fibrously normal to the pyrite faces. The chlorite zones is not so well developed and there is corresponding feeble development of the magnetite zo In connexion with this feeble development of the magnetite zone, it is noticed that in the rock matrix itself authigenous magnetite is not very abundantly developed.

The interior of the compound crystals is very punctate, the cavities being filled with chalcedony, chlorite or rock matrix.

The rock matrix: (a) In the deep olive green bands, consists of the most part of green chlorite, having the usual properties very abundantly developed, and consequently of a deeper colour. It has the same pleochroism and occasionally forms good lath-shaped crystals with "pseudo-hexagonal" terminations. Scattered irregularly throughout and locally concentrated is quartzose material; this appears to be for the most part of detrital origin, but it has suffered some recrystallization, and some may be chalcedonic. Generally the total amount of quartzose material present is small, approximately 5-10 p.c. by volume, though it locally develops in greater amounts.

Throughout this chlorite-quartz materisl are irregularly scattered small globular masses of a yellowish-brown carbonate mineral. It possesses no good crystal outlines. It is assumed to be a mixed iron-manganese carbonate since manganese is present in a very readily oxidisable form, and iron is suggested by the colour. In size the globular bodies vary from 0.015 mm. to 0.04 mm. They are not abundant in these darker bands.

The small colourless garnets, identical with those already described are fairly frequent, and have a uniform distribution throughout the band. They form approximately 10-15 p.c. of the rock. They vary in size from 0.005 mm. to 0.017 mm., with an average of 0.015 mm. The largest crystals occasionally show an isotropic character in section.

Magnetite occurs in very small grains varying from 0.005 mm to 0.025 mm. Some of the larger grains possess euhedral and subhedral shapes and are authigenous in origin. Most of the smaller ones, however, are very irregular in shape and often quite rounded and are probably allothigenous.

The very small reddish-brown euhedral garnets also occur.

(b) The paler green band: is composed of the same minerals as (a) and the differences are as follows. It is of finer grain and somewhat more compact. Quartzose material is not so abundant, and it tends to be localized in patches. The chlorite is not developed to the same extent, but there is a marked increase in the amount of the brown carbonate mineral. In addition there is a fair amount of a paler, almost colourless carbonate (normal dialogite) intermixed with it. Garnet is still fairly common, but the magnetite is not as abundant and appears to be chiefly of the small allothigenous type. The small reddish garnet also occurs.

The junction between the darker and paler green bands is fairly abruptly marked in hand specimen, and microscopically, the change is quite

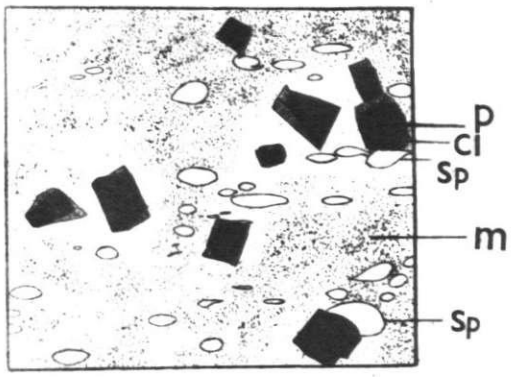


Fig. 21. Pyritiferous layer in lower portion of Bluestone. East slope of Diphwys.

To show the relationship of pyrite crystals and spheroidal bodies of "ore" material to mudstone matrix.

P: pyrite; Cl: chlorite zones surrounding the pyrite; Sp: spheroidal bodies of "ore": m: magnetite-bearing matrix.

Magnification x 40 diams.

sharp from the less compact darker band to the more compact lighter band, by the sudden increase in the amount of carbonate material, and by the oncoming of almost colourless dialogite. The junction is more abrupt at the upper side of the paler band.

A pyritiferous layer in the lower portion of "Bluestone"; on the eastern slope of Diphwys: a bluish-grey mudstone containing pyrite crystals 1 mm. to 2 mm. in size scattered throughout. The pyrite occurs through a thickness of about half an inch and its upper and lower limits are parallel to the bedding.

Under the microscope the pyrite crystals are seen to be isolated simple euhedra. The present good shapes (typical sections of cube crystals). They are surrounded by the familiar zones, the material of which consists almost entirely of green chlorite, chalcedonic silica being practically absent (Fig. 21). Associated with the chlorite are zones of magnetite adhering to the walls of the crystal, and in every way similar to those already described. These are not of universal occurrence, and many faces possessing a surrounding chlorite zones have no magnetite zone, and rarely, a magnetite zones has no chlorite zone succeeding it. Haematite has occasionally developed along the outer margin of the chlorite zone, and it is also sometimes present as a thin veneer on some of the crystal faces themselves. This is probably an alteration product. The green chlorite forming in bulk of the zones is identical with that already described in these zones.

As the rock matrix is typical "bluestone", the account of it will be placed in the setion on the ordinary mudstones.

Another pyritiferous band (Hendre Mines, N.W. slope of Moelfre) is observed in the lower portion of the "bluestone" about 6 inches above the top of the ore.

The hand specimen (see Pl. 4 fig. 4) is a finely laminated mudstone, consisting of rapid alternations of a darker green mudstone and a paler, grey more compact material. For the most part the laminae are of a similar thickness, $\frac{1}{16}$th to $\frac{1}{10}$th inch. They occasionally reach $\frac{3}{16}$ths or $\frac{1}{4}$inch and more rarely $\frac{1}{2}$ inch in thickness. The laminae are distinctly marked off from one another, and they are remarkable for their very regularly parallel, plane character. The similarity between the bands of paler compact materials and the material of the true ore-band is apparent especially in the thicker layers.

The pyritiferous portion is $^{9}/_{16}$ths inch thick (cpmprising eight to ten laminae). Although at first sight the pyrite crystals appear to be evenly scattered though this thickness, on closer examination, they are all seen to fall into four layers, parallel to the bedding, and more intimately with the darker mudstone material than with the paler compact "ore" material.

The pyrite crystals are very similar to those described above. They occur in isolated euhedra of sizes varying between 0.1 mm. and 3.5 mm. In section they have the usual rectangular, trapezuim and triangle outlines typical of euhedral pyrite. They are fairly abundant forming 10-15 p.c. of the pyritiferous band. They are surrounded by the usual zones, in which chalcedony predominates over the chlorite. When both occur their relationships are similar to those indicated before. The zones surrounding the larger crystals, tend themselves to be large, often equal to half or more of pyrite crystal which it surrounds. The zones surrounding the smaller crystals, are themselves smaller relatively and in them chlorite predominates, often to the extent of being the only constituent. The magnetite zone is not well developed, but when it does occur it is in intimate association with chlorite, as was the case before. The larger crystals appear to contain inclusions of euhedral magnetite, these standing out as small black crystals in reflected light in contrast to the brassy colour of the pyrite. These have the same size as the magnetite crystals of the matrix and this indicates that the two minerals crystallized contemporaneously.

On the S.W. slopes of Rhinog Fach pyrite crystals are distributed irregularly in a pale purplish-cream compact "ore" band, occurring interstratified with the "bluestone" just above the ore.

The pyrite crystals are isolated, euhedral and contain minute inclusions of magnetite. They have imperfectly developed chlorite-silica zones surrounding them, which usually exist on only two (opposite)sides (in section). The zones consist of fibrously intergrown chlorite and chalcedony which have the same relationships as in previous cases. The narrow magnetite zone is frequently present.

The rock matrix consists of an intimate intergrowth of dialogite and spessartite similar to the "ore" rock, and scattered throughout occur small magnetite euhedra. Occasional ill-developed masses of chlorite occur, but the small reddish-brown garnets are entirely absent.

LL. Petrology of the Pyrite-bearing strata.

The materials which crystallized to form pyrite crystals in these rocks were undoubtedly of a sedimentary origin. This conclusion is deduced from the invariable occurrence of the crystals in planes parallel to the bedding of the rocks. The best example of this is the pyrite-bearing mudstone immediately below the ore which is present at the same bedding horizon throughout the area. Again, even within this relatively thick band of pyrite-bearing rock, the pyrite crystals, themselves, are frequently concentrated in several thin layers parallel to the bedding, and the layers in which they occur themselves show more iron-rich tendencies than the intervening layers in which the pyrite crystals tend to be absent. These iron-rich tendencies are shown in the darker green colour, due to the greater abundance of chlorite and particularly of magnetite and corresponding decrease of manganese carbonate and detrital quartz ~~(see D)~~. Even where the pyrite band is badly cleaved, the localization of the pyrite crystals along these darker, more iron-rich bands is still clearly to be seen. In the "bluestone", the occurrence of the pyrite crystals in thin impersistent layers parallel to the bedding is again clear, and the tendency for them to occur in the darker laminae containing less dialogite is again significant.

This occurrence of the pyrite crystals always in planes parallel to the bedding, and again nearly always in the darker laminae and bands, without ever and tendency to transgress them even slightly, is accepted as evidence of the sedimentary origin of the sulphide.

The age of the crystallization of the pyrite crystals is deduced from a consideration of the zones of secondary material surrounding them and described above. A. Harker[1] described zones of secondary chlorite and silica surrounding pyrite in slates, and he regards the zones as having been formed by the infilling of spaces, caused by the stretching out of the rock matrix around the rigid pyrite crystal during cleavage. According to his view the silica zone post dates the pyrite, and is contemporaneous with the cleavage, while the pyrite is pre-cleavage. However many of these pyrite-bearing rocks show no cleavage structures and the pyrite occurs surrounded by chlorite-silica zones having no elongate arrangement in eyes parallel to any given direction.

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[1] On "Eyes" of Pyrite and other Minerals in Slate". Geol. Mag. Dec.III. Vol.VI. 1889. p.396-7.

The zones are regarded as being formed by the infilling of spaces formed around the pyrite by secondary material from circulating solutions. These spaces were the direct result of the contraction in volume consequent on the crystallization of the pyrite. Such spaces could only be formed after the rock matrix had attained a rigid state, otherwise loose and unconsolidated material would have adapted itself to the decreasing volume, and infilled the spaces as they were being formed. The junctions of the secondary materials infilling the zones with the rock matrix are abrupt and indicate that the rock matrix made no effort whatsoever to adapt itself to the decreasing volume caused by the crystallization of the pyrite. Such a condition could only be possible if the rock materials were in a rigid consolidated state. Thus the crystallization of the pyrite is dated at some period after the consolidation and induration of the rock.

Some examples are noted in which pyrite crystals are disrupted by the cleavage, and so in common with the pyrite-bearing slates, the pyrite of these rocks is pre-cleavage in age. The cleavage was due to the earth movements resulting in the uplift of the thick lower Palaeozoic deposits, and therefore the crystallization of the pyrite was pre-these earth movements. The pyrite crystallized when the sediments containing the original sulphide sank to great depths. The actual crystallization was induced by the downward pressure exerted by the great thicknesses of superimposed materials, this agreeing with the principle that minerals of low specific volume and a high degree of symmetry crystallize under great "hydrostatic" pressure.[1]

The indications are that the sulphide was originally deposited in a finely disseminated state throughout the sediment, and that when crystallization was induced this was diffused towards the points of actual crystallization now represented by the pyrite crystals themselves. Thus the first stage of these metamorphic changes is represented by the localization of the iron sulphide itself before its transformation into pyrite, into concentrated clots to the exclusion of the rock matrix, in a similar manner to the formation concretionary structures which in some rocks are due to processes of diffusion and crystallization. The transformation of ordinary iron sulphide to crystalline pyrite involves a considerable contraction in volume which ~~result~~ would then result in the formation of spaces now infilled with secondary material around the actual crystals. Ordinary black amorphous iron sulphide (approximating to

[1] Van Hise, C.R. A Treatise on Metamorphism". Monog. 47. U.S. Geol. Surv. p. 215, 360.

FeS)[1] is precipitated from solution in natural waters and it has often been recorded occurring in a finely divided state, in for example, Coal Measure Shales and the Rhaetic Black Shales. The crystallization of pyrite FeS_2 from such material would apparently involve the liberation of the iron (according to $2FeS (= FeS_2 + Fe)$; thus, if liberated, could form, under these pressures, magnetite, by combination, with water, in what would be a zone of dehydration. The almost invariable presence of authigenous magnetite and pyrite in the pyrite-bearing rocks, their tendency to reciprocal relations in the Grits (see table and pp. 44), and especially the occurrence of minute magnetite euhedra enclosed within larger pyrite crystals indicates contemporaneous crystallization of the pyrite and magnetite, and seem to bear out a reaction of this nature. Such a reaction could be represented thus:-

$$6FeS + 2O_2 = 3FeS_2 + Fe_3O_4$$

Excessive oxidation of the sulphide thus:-

$$3FeS + 5O_2 = Fe_3O_4 + 3SO_2$$

would result in the formation of magnetite at the expense of the pyrite, a condition represented by large authigenic magnetite, and low pyrite percentages in many of the grit heavy residues. On the other hand it appears that pyrite would never be formed without magnetite, a condition that seems to be borne out by the facts. [The necessary oxygen required to satisfy these reactions would be available in the water given off from the aluminous minerals which are recrystallizing at this stage.]

With regard to the zonal developments surrounding the pyrite crystals, the materials forming them obviously depended on the nature of the circulating solutions from which they were derived. The zones have the following general characteristics:

(1) Frequently they are composed only of chalcedony and chlorite; the proportions of the two vary considerably. (Fig. 14).

(2) Although chlorite may often occur to the virtual exclusion of silica (e.g. Figs. 18A and ~~pp.~~ 21), silica hardly ever occurs without chlorite.

(3) When both occur they are fibrously intergrown, with the silica occupying the internal portions of the zone, adjacent to the pyrite, and the chlorite the external portions. (Figs. 14, 15 16 and 17.).

(4) When silica is absent, a regular zone of magnetite, often intervenes between the chlorite zone and the pyrite face (Fig. 18).

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[1] The composition of these finely divided amorphous iron sulphides is doubtful, but it is generally admitted that they approach FeS.

This tends to be absent when the silica zone is developed (Figs. 18 & 19).

(5) Between the magnetite and the chlorite zones is developed an irregular zone of yellowish-brown chlorite (Fig. 18). This is absent when silica is developed.

(6) Occasionally a zone of iron carbonate (siderite) is developed. It is sometimes developed when the silica zone is absent; it then occurs on the internal side of the chlorite zone, and is succeeded by the magnetite zone adjacent to the crystal (Fig. 20); or it may occur together with chlorite and silica (Fig. 19) when it takes up a position between the chlorite and the silica zones.

(7) All constituents develop fibrously intergrown with the fibre-lengths orientated at right angles to the crystal faces.

Now, the formation of the surrounding space would synchronise with the crystallization of the pyrite, and that space would be filled up progressively as it was formed. The part of the existing space to be first formed would be that furthest away from the centre of crystallization, and the last part, that nearest the centre of crystallization, since contraction took place towards that centre. That is the portions of the zone immediately surrounding the crystal were the last formed. Since crystallization of the secondary material took place progressively with the formation of the space, the order of crystallization of the secondary constituents of the zone is represented by the sequence from the external parts of the zone inwards towards the pyrite, that now adjoining the pyrite being the last to crystallize.

From the minerals present in the zones it is deduced that the materials present in the circulating solutions were: alumina, iron compounds, silica, and rarely carbonic acid. Upon the relative amounts of these constituents depended the final composition of the zone surrounding the pyrite.

From the evidence (1 to 3 above) it will now be seen that the silica crystallized out after the chlorite, and consequently it represents excess pf silica over the metallic oxides, with reference to the amounts of these minerals required to form the green chlorite.

When the magnetite zone is present it was the last to crystallize, and since no silica is associated with it, it represents an excess of the metallic oxides (chiefly iron) over silica with reference to the amounts necessary to form green chlorite, the final stages being marked by the crystallization of residual iron oxide (magnetite). The brown chlorite (5)

crystallized after the green chlorite and before the magnetite; it is assumed to be a iron-rich chlorite, and consequently represents the increasing enrichment of the solutions in iron, an enrichment finally resulting in the crystallization of magnetite. Sometimes, this brown chlorite is actually seen merging gradually with the green chlorite externally, thus indicating this enrichment. A significant fact is that the magnetite zone has only been observed in these rocks, in which the matrix has developed large quantities of authigenous magnetite, i.e. where a rock very rich in iron could give circulating solutions rich in iron. This is very common in the pyrite band below the ore. When magnetite is not well developed in the matrix (e.g. "Bluestone Grit" from Cwm-yr-Afon) the magnetite zone is not developed.

Since the siderite zone is developed around crystals when silica is both present and absent, its formation clearly does not depend on iron-rich or silica-rich solutions. It clearly separates immediately after the green chlorite, whether or not silica crystallizes, and its separation appears to depend almost solely on the presence of carbonic acid.

Thus the sequence of mineral crystallization in the zones surrounding the pyrite may be summarized as follows:

A. Carbonic acid absent:

1. Solution SiO_2 rich: green chlorite $\longrightarrow$ silica.
2. Solution iron-oxide rich: green chlorite $\longrightarrow$ brown chlorite $\longrightarrow$ magnetite.

B. Carbonic acid present:

1. Solution SiO_2 rich: green chlorite $\longrightarrow$ siderite - silica
2. Solution iron-oxide rich: green chlorite $\longrightarrow$ siderite $\longrightarrow$ magnetite

The origin of the mudstone matrix of these pyritiferous rocks and changes that have taken place in it are largely similar to those of the ordinary mudstone, and they will be discussed in the section dealing with these mudstones. It is, however, interesting to note, with regard to the pyrite band below the ore in particular: the dark green colour reflecting the abundant chlorite, and the abundant authigenous magnetite, both of which facts indicate the original very iron-rich character of the sediments being laid down. This is very noticeable in the case of the pyrite band of the Hendre locality (pp.106-7). The pyrite was intimately associated with two dark green bands, while the intervening paler green band was relatively pyrite-free. The abundant chlorite and pyrite in the darker band are largely replaced by manganese carbonate in the paler band, this indicating the general diminution

of the iron content in the pyrite-free bands. The same feature is noted when pyrite occurs in the laminated "bluestone". The pyrite nearly always occurs in the thin darker bands, while the paler carbonate-rich bands tend to be always pyrite free.

With regard to the precipitation of the iron sulphide itself, it seems impossible to appeal to the normal method by reduction of iron sulphate in solution by decaying organic matter. The associated rocks show no trace of organic or carbonaceous matter, and the total absence of fossils in rocks entirely suitable for preservation indicates that for some reason life was impossible in these waters. This would probably be due to the abnormally high percentages of manganese in solution, as suggested by the precipitation of carbonates from these waters to form a rock which contained many times more manganese than iron, whereas the normal ratio of iron:manganese is about 40/70:1[1]. W.E. Brenchley[2] quotes work by Loew and Gawa (1902) who found that abnormal manganese concentrations had a toxic effect on plants. They found that "0.25 per cent = $\frac{1}{400}$ $MnSo_4$ (anhydrous) kills pea plants in five days and that the green colour is gradually affected with more dilute solutions. Barley and soybeans were grown in nutritive solutions with either iron or manganese sulphate or both (0.01 per cent $FeSO_4$, 0.02 per cent $MnSO_4$, .01 per cent $FeSO_4$ + 0.02 per cent $MnSO_4$). At first the growth was increased by the action of two salts together, but eventually the shoots turned yellowish, and assimilation was depressed, so that decreased nutrition led to relaxation in the speed of growth, indicating the toxic action due to the manganese sulphate." They found that the presence of iron seems to counteract the effects of manganese,[3] but here the amount of iron appears to be very small. There, therefore, appears to be good reason to believe that no organic matter existed in these waters, and that iron sulphide could not be precipitated by such means.

It must therefore have been formed by the direct action of soluble sulphides on soluble iron salts. Van Hise[4] states sodium carbonate, one of

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1 Beyschlag, Vogr and Krusch, "Ore Deposits". Vol. Macmillan 1914. p.979.

2 "Inorganic Plant Poisons and Stimulants". Cambridge 1914. p.81.

3 Op. cit. p.81.

4 A Treatise on Metamorphism". Monog.47. U.S. Geol. Surv. p.1107.

THE OCCURRENCE OF SPHAERODIALOGITE IN THE MUDSTONES.

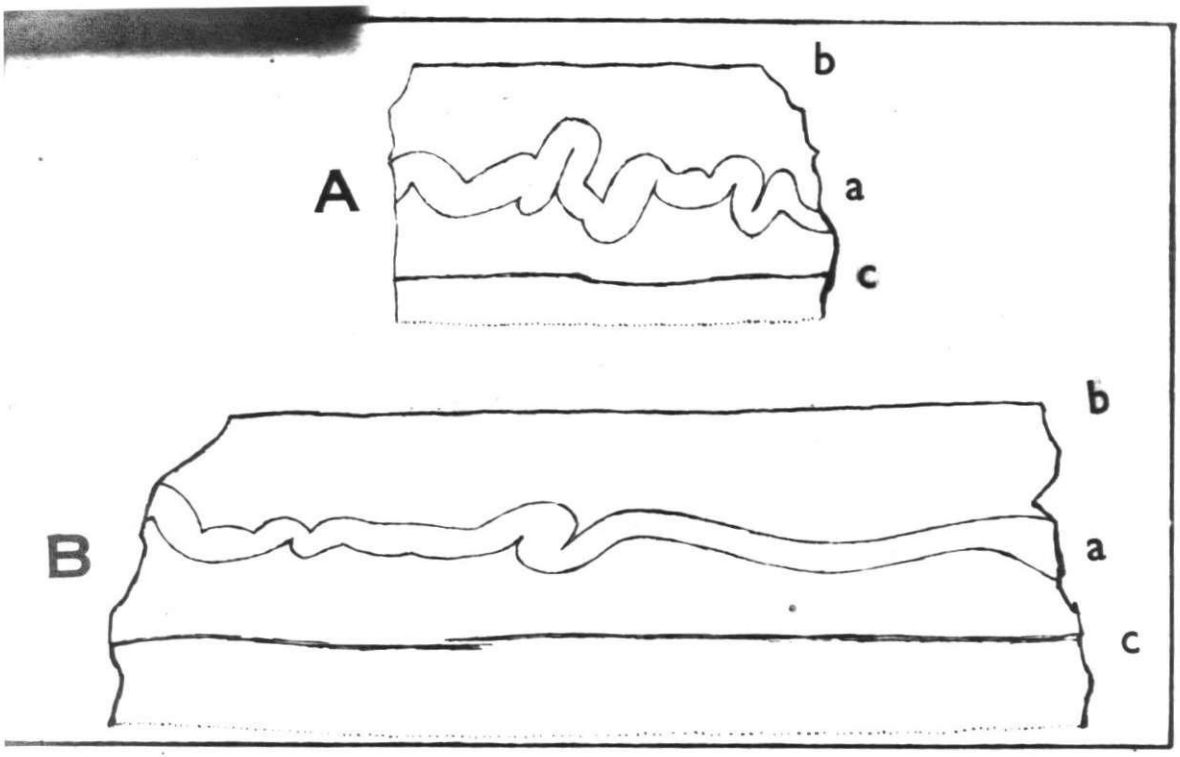


Fig. 22. The "folded" nature of the sphaerodialogite band.
St. John's Church, Barmouth.

A. At right angles to the axis of the "folding".

B. Approximately parallel to the axis of the "folding".

a: sphaerodialogite band; b: junction of the blue-grey mudstone with the overlying grit; c: a bedding layer within the normal mudstone below.

Natural size.

The Occurrence of Sphaerodialogite in the Mudstones.

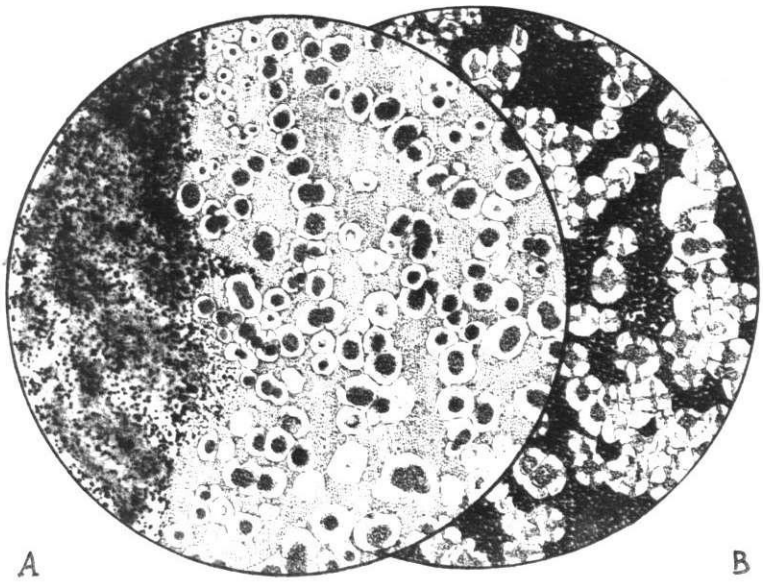
A relatively persistent but thin layer, composed mainly of sphaerodialogite, was proved at the same horizon ($^1/2$ - $^3/4$ inch below the "Bluestone Grit") (see p. 9) at two localities - St. John's Church, Barmouth and at the lower end of the manganese workings on the western side of the Cwm Mynach Valley. In addition, pale green bands, distinguishable with difficulty from ordinary mudstone, were found, on being sectioned, to contain sphaerodialogite, and the irregular white blotchy patches, distributed throughout and above the "bluestone" and throughout the whole area, are composed of massive sphaerodialogite. The characters and relationships of the sphaerodialogite layer at the St. John's Church locality, Barmouth, are as follows:

Macroscopic characters. It consists of the normal blue-grey mudstone, containing striped irregularly lenticular developments of a paler greenish-grey mudstone, the thin regular plane striping, usually so characteristic of the "bluestone" not being very well marked. The paler lenticles vary up to half an inch in thickness, stringing out into thin layers within a space of two or three inches. Occasionally, regular thin bands of uniform thickness are observed, which approximate to the regular plane bands of the striped bluestone.

Scattered throughout the mudstone occur irregularly shaped blotches of a white material. They are devoid of any regular shape, but are usually aligned with their greatest linear development parallel to the bedding of the rock. They frequently show transition into the blue-grey mudstone through material similar to the greenish-grey mudstone. They will be referred to in later description as "irregular white blotchy developments". These are characteristic of these rocks and occur in both mudstones and grits.

Upwards, the blue-grey mudstone is succeeded by a layer of grit. The junction between the two is abrupt and forms a plane of ready parting. This plane is rppresented by b in Fig. 22

Approximately 0.6 - 0.7 inches below this occurs a thin band, very regularly developed, having a thickness of 0.15 - 0.20 inches (Band a in Fig. 22). It is contorted into a series of minor folds, sometimes



A B

Fig.23 Sphaerodialogite band; St. John's Church, Barmouth.

A. Spherulites of sphaerodialogite set in a chloritic ground-mass. Note: (a) the interior area with included argillaceous material, (b) the interference of the spherulites. The junction of the band with the normal blue grey mudstone is well demarcated.

B. The same, with nicols crossed, to show the well marked black-cross extinction. Magnification x 40 diams.

gentle, and sometimes sharp and overfolded, and occasionally with both limbs of the fold pressed tightly together. (Fig. 22). The overfolds have a maximum deviation from the vertical of up to 15°, and the direction of overfolding is more or less constant. Fig.A is along a plane at right angles to the direction of folding and shows the maximum effects, while Fig.B being more or less parallel to that direction shows only gentle undulations. In the field the direction of the overfolding was inclined approximately towards E 6°N.

Immediately above and below this folded band, the bedding of the rock is more or less plane (bands b and c in Fig. 22). The folding could not have been formed by post-consolidation lateral movement, since differential minor folding of a thin band in a generally undisturbed sequence is hardly likely. The only alternative seems to be contemporaneous deformation of the bed, immediately on being formed and before the deposition of the succeeding mudstone. This might be due to wave or current action, the direction of the overfolding giving the direction of movement of the waters.

This band differs from the normal mudstone in being a greenish-grey in colour and is minutely speckled with small spherical bodies of a white material, similar to that present in the irregular blotchy developments.

Microscopic characters: The folded band of speckled green-grey material. The band consists of aggregates of spherulites set in a fine-grained, bright-green chlorite matrix. (Fig. 23).

The spherulites vary in size from 0.080 mm. to 0.135 mm. in diameter, an average being 0.110 mm. They are colourless or pale cream when fresh. The central area is crowded with a paste-like aggregate of argillaceous inclusions which have a "dirty" greyish-brown appearance. A thin layer of similar material usually lines the exterior margins of each spherulite. The central region with included material is usually well marked from the relatively clear portion surrounding it and the junction between the two regions is distinct. The relatively clear portion surrounding this central region contains very thinly dispersed inclusions of a similar character, and these decrease in abundance outwards, the region immediately inside the external margin being entirely free from such included material. The diameter of the distinctly marked central

core is approximately one half to two thirds that of the spherulite itself. Sometimes this internal portion has a homogeneous appearance, but frequently the outer portion is more pronounced than the central portion.

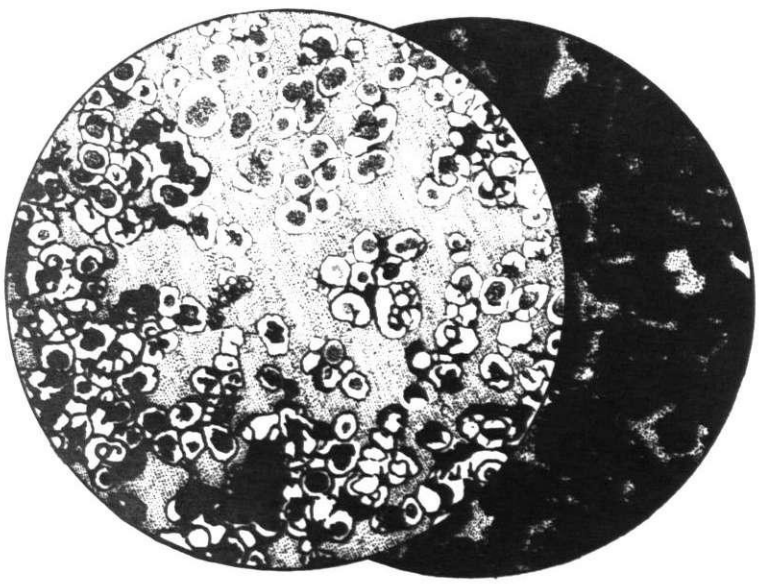
Frequent irregular radial and concentric cracks traverse the spherulites, but they are seldom well-defined.

In ordinary light, no trace of radial development is seen. However, with the nicols crossed, the black cross extinction phenomenon, characteristic of radially disposed aggregates is well displayed (Fig.238). When examined with only the lower nicol in position, a faint relief brush, practically indistinguishable in the stationary position, is seen to revolve as the nicol itself is turned. From this it is seen that the direction of elongation of the crystal fibres is parallel to the optic axes of the mineral, since the greatest relief is displayed when they are orientated with their length at right angles to the direction of vibration of the polariser. The spherulites are thus composed of radially developed fibres, so slender as to be indistinguishable as individuals.

The mineral has a refractive index varying from somewhat below to somewhat above that of the accompanying interstitial chlorite, and the birefringence is approximately 0.20.

When the spherulites are developed as isolated individuals, they have a more or less circular outline in section. This, however, is very rare. The spherulites usually occur in aggregates and the individuals have interfered with one another during growth. The junctions between such interfering spherulites are approximately plane surfaces i.e. straight lines in section, and when many individuals constitute such an aggregate, the inner ones possess polygonal outlines, The amount of interference depends on the distance apart of the centres of growth. They are often so close that the central areas of included material coalesce; where less interference has taken place these regions are still separate. The junction plane between two such interfering spherulites is at right angles to a line joining the two growth centres of the spherulites. The line of junction in section is usually marked by a thin darker line, due to a concentration of material, similar to that included in the central region, along the plane of contact.

The ground mass in filling the interstices between the spherulites consists essentially of a very fine-grained intergrowth of green chlorite,



A B

Fig. 24. Sphaerodialogite Band; St. John's Church, Barmouth.

A. Progressive oxidation of the spherulites.

B. The final stage of the oxidation is the complete alteration of the spherulites to pyrolusite. Magnification × 40 diams.

quartz and rare lath-shaped crystals of sericite. The chlorite forms by far the greater proportion of the matrix. It is green with a distinct pleochroism from pale yellow-green to bright green and its optical properties are similar to those described for the chlorite in the matrix of the grits and in the mudstones, and the same lath-shaped crystals with "pseudo-rhombohedral" terminations are observed. The silica is clear and has a mosaic-like intergrowth with the chlorite. Occasional euhedra of magnetite, about 0.002 mm. in size occur.

Chemical analysis (see p.123) proves quite conclusively that the material composing the spherulites is manganese carbonate (dialogite) and this occurrence is, therefore, termed sphaerodialogite.

Changes in weathering: On weathering, changes occur both in the spherulites and in the chlorite ground mass. The spherulites change by the break down of the dialogite and the formation of manganese dioxide (pyrolusite). Fig.24A shows the progressive oxidation of the spherulites. The first portion to break-down is the exterior margin of the spherulite. Then a ring of pyrolusite forms by the break-down of the exterior portion of the internal area with included matter, progressive alteration resulting in the complete break-down of this central area. Oxidation also takes place along the irregular cracks which traverse the spherulites. Fig. 24B shows the final stage in the decomposition, when the whole of the spherulite has been oxidised. Thus the first portions of the spherulite to be affected are those portions containing included argillaceous dust, on the exterior margin and in the central area, while the intermediate, more or less inclusion-free portion of the spherulite, is the last to undergo change. It thus appears that the presence of the included material renders the carbonate in which it is included, more susceptible to oxidation, while the inclusion-free carbonate is much more stable.

The chlorite is much more stable than the carbonate and does not begin to break down until some time after the commencement of oxidation of the carbonate. The changes undergone result in the formation of an indefinite yellowish to yellowish-brown chlorite material.

The normal blue-grey mudstone: is similar to the typical "bluestone" mudstone described in another section and it consists essentially of a very fine-grained admixture of detrital quartz grains, chlorite and sericite,

with subordinate magnetite and spessartite garnets. The detrital quartz grains vary from 0.01 mm. to 0.02 mm.; the chlorite laths from 0.008 mm. to 0.02 mm. long and from 0.005 mm. to 0.008 mm. wide; the magnetite crystals from 0.006 mm. to 0.025 mm.; and the garnets from 0.007 to 0.012 mm. The quartz forms about 50 - 60 p.c. and is largely of detrital origin. It is all of the same type - a clear colourless variety. The chlorite has the same optical properties as has that already described from these rocks. It makes up about 30 p.c. of the rock.

The spessartite garnets are largely euhedral and colourless and identical with those described from the accompanying grits and mudstones. They are not frequent and only make up a very small proportion of the rock. The minute reddish-brown garnets also occur.

Magnetite is abuntantly developed in good octahedra, and is authigenous. It makes up 5 - 8 p.c. of the section.

Locally, small areas of carbonate material are developed. This carbonate material is the same as that in the spherulites except that it is devoid of the well-defined structures and it is intimately intergrown with the other constituents of the rock.

On weathering, the rock surface becomes covered with a thin film of blue-black pyrolusite, and in the less advanced state of decomposition the chlorite takes on a yellowish-brown colour. The manganese thus shown to be present occurs chiefly in the dialogite, chlorite and spessartite.

The paler-greenish grey mudstone: (This material when treated with hydrochloric acid gives off fairly abundant carbon dioxide). It consists essentially of carbonate (dialogite by chemical analysis), pale green chlorite, and some spessartite, magnetite and haematite. The dialogite is by far the most abundant constituent, making up 60 - 70 p.c. of the section. It occurs in small globular grains, varying in size from 0.010 mm. to 0.025 mm. These, although they have a similar external shape, are not true spherulites, and they do not give black-cross extinction. No crystal form whatsoever is distinguishable and interference one with another often gives individuals a polygonal outline in section.

The chlorite is interstitial and is pale green and similar to that occurring above. The spessartite garnets are not easy to distinguish

because they are similar in appearance to the dialogite globules. They are recognized by their smaller size (0.006 - 0.012 mm.), their euhedralism and their uniformly greater refractive index. They are not abundant. The small reddish-brown garnets again occur. Magnetite crystals are less abundant, and this decrease in the amount of opaque matter, may explain the paler colour of the band itself.

The junction between the paler greenish-grey material and the darker bluish-grey material is very distinct and can be seen even under high powers, and especially under crossed nicols when the quartz of the latter stands out clearly from the dialogite of the former.

The "irregular white blotchy developments." These consist of developments of spherulites of sphaerodialogite set in a ground mass of green chlorite in similar manner to that described in the sphaerodialogite layer. There however, the proportions of sphaerodialogite to chlorite remain approximately the same throughout the band. In this case there is considerable variation in these proportions. The internal portions, i.e. those portions which are white in hand specimen, consist of sphaerodialogite to the virtual exclusion of green chlorite. Here the spherulites are so closely packed as to be almost indistinguishable. The narrow development of included material on the exterior margins of the spherulites is often non-existent, and the boundaries of the spherulites then merge completely into one another. The individuals are recognized by the presence of the internal area of included argillaceous materials and by the faint black crosses displayed between crossed nicols. The degree to which the internal darker region is developed varies, and is sometimes very faint, when the individuals are very difficult to distinguish, and at other times very pronounced.

In the external margins of these blotchy developments, the chlorite is well developed, and these portions take on an appearance identical with that of the normal sphaerodialogite band. Occasionally large patches of chlorite with no accompanying sphaerodialogite are developed.

Scattered throughout these blotches are cavities and irregular veins filled with secondary chlorite, chalcedonic silica, and secondary carbonate. All these materials have a fibrous development, with the fibres aligned at right angles to the walls of the vein or cavity. When the veins

reach the margin of the blotchy development, i.e. its junction with the mudstone, they cease abruptly. This proves that that they are not due to movement and they are regarded as being contraction phenomena due to the drying of the material forming the blotchy development.

The passage of the blotchy developments into the normal blue mudstone is well marked, and is distinguished under the microscope by the sudden ceasing of carbonate development, and the sudden oncoming of detrital materials. The apparent transition from white material to blue-grey mudstone, through material similar to the greenish-grey mudstone, noted above, is due to the increase in chloritic material towards the outward margin of the blotchy development, and not to admixed detrital material.

Chemical composition of the sphaerodialogite band. When the powder obtained by crushing the sphaerodialogite band ( ) is treated with dilute hydrochloric acid, it is found that the dialogite is completely soluble, while practically all the chloritic matrix material remains behind as insoluble residue. Using this method, therefore, it is possible to isolate sphaerodialogite material for analysis. The following are analyses of the soluble portion and of the insoluble residue:-

	I	II		III
SiO_2	1.23	56.89		10.4
Al_2O_3	3.24	14.42		3.6
Fe_2O_3	1.32	0.31		15.4
FeO	5.15	13.34		
MnO	44.94	1.69	Mn_2O_3	32.3
MgO	0.34	4.91		0.9
CaO	5.17	1.24		8.6
H_2O	-	5.96		0.3
Na_2O K_2O	2.51	1.41		-
CO_2	35.79	-	Loss on ignition	29.4
	99.69	100.17	P_2O_5	0.1
				101.0

I. Soluble portion - mainly sphaerodialogite.

II. Insoluble portion - mainly chlorite with subordinate quartz.

III. "Spherulites with Radiolaria in Rhombohedral Carbonates, Santo Domingo (Portugal)": E. Spencer, Q.J.G.S. Vol. lxxxi. (1925). p.684.

Approximate Mineral Composition: Composition of the carbonate calculated by regarding all the MnO, FeO, MgO and CaO as being present. These require 35.33 per cent CO_2 to form a mixed carbonate and the amount estimated by analysis is 35.79 per cent. The SiO_2, Al_2O_3 and Fe_2O_3 would be represented by the clayey aluminous material and a small amount of soluble chlorite.

	I		III
SiO_2	1.23		10.4
Fe_2O_3	1.32		
Al_2O_3	3.24		3.6
$FeCO_3$	8.29		22.2
$MnCO_3$	72.79		47.0
$MgCO_3$	0.62		1.9
$CaCO_3$	9.23		15.2
Na_2O K_2O	2.51	H_2O	0.5
	99.23	Calcium phosphate	0.2
			100.8

The spherulites, therefore, consist very largely of manganese carbonate, the remainder consisting for the most part of iron carbonate and calcium carbonate in equal proportions. They thus merit the name: sphaerodialogite In the spherulite rock described by Spencer the spherulites consisted of manganese carbonate in lesser quantity, while iron carbonate and calcium carbonate in approximately equal quantities were present in greater amount than in the present case.

With regard to the composition of the insoluble residue, if the very small amounts of sericite and magnetite present be neglected, it is possible to calculate an approximate composition for the chlorite. This is done by calculating the ratios RO : R_2O_3 : H_2O and neglecting the silica since considerable quartz is present.

R_2O_3	Al_2O_3	14.42/102	÷	102	0.142	0.144	2
	Fe_2O_3	0.31/160	÷	160	0.002		
RO	MnO	1.69/71	÷	71	0.024	0.209	3
	FeO	13.34/72	÷	72	0.185		
	MgO	4.91/40	÷	40	0.122	0.144	2
	CaO	1.24/56	÷	56	0.022		
H_2O	H_2O	5.96/18	÷	18	0.330	0.330	$4^2/3$

That is the composition can be represented as $2(Al\ Fe)_2O_3.2MgO.3FeO.4^2/3\ H_2O.(xSiO_2)$. Now if the FeO and MnO be present in the mixed chlorite as daphnite, and the CaO and MgO as amesite, and the residual FeO as ferro-antigorite:

Amesite:	$3 \times Al_2O_3$	2MgO	$2H_2O$	(SiO_2)
Daphnite:	$3 \times Al_2O_3$	2FeO	$2H_2O$	(SiO_2)
Ferro-antigorite:	$1 \times$	3FeO	$2H_2O$	$(2SiO_2)$

At + Dn + FeAnt $6Al_2O_3.6MgO.9FeO.14H_2O.(8SiO_2)$

$\div 3$ $2Al_2O_3.2MgO.3FeO.4^2/3H_2O\ (2^2/3SiO_2)$ which is the same as the calculated formula above.

Therefore the composition can be represented, using Winchell's classification by: $(Dn_{50} + At_{50})_6 + (Ant_0 + FeAnt_{100})_1$

According to the graphical representation given by Winchell[1], a chlorite with the composition represented above falls into the group of aphrosiderites and shows transitions to the ripidolites.

The composition of the chlorite was recalculated to 100 per cent in accordance with the above formula, and it is given below with other analyses for comparison

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1 Elements of Optical Mineralogy. Vol.II. New York (1933). p.280.

	I	II	III	IV
SiO_2	21.50	24.97	25.72	23.3
Al_2O_3	27.03	23.76	20.69	21.4
Fe_2O_3	0.58	1.55	4.01	2.0
FeO	25.01	26.86	27.79	28.6
MnO	3.17	"	"	0.3
MgO	9.21	10.81	11.70	10.7
CaO	2.32	"	"	"
H_2O	11.18	10.71	10.05	10.5
	100.00	98.66	99.96	96.8

	V	VI	VII	VIII
SiO_2	26.07	23.52	21.35	22.35
Al_2O_3	27.90	22.35	17.70	25.14
Fe_2O_3	2.59	1.92	11.57	
FeO	23.26	28.78	36.81	34.39
MnO	"	0.32		
MgO	8.72	10.79	3.90	6.41
CaO	"	0.39		
H_2O	10.56	11.28	8.78	11.25
	99.85	99.35	100.11	99.54

I. "Aphrosiderite" from the sphaerodialogite rock. St. John's Church, Barmouth.

II. "Aphrosiderite" cited by Orcel[1] (p.359); Larsen, E.S. and Steiger, G. "Mineralogic Notes (Aphrosiderite, thuringite, griffithite)". Journ. of the Wash. Acad. Sci. Vol.VII. (1917). p.6.

III. "Aphrosiderite" cited by Orcel[1] (p.359); Erlenmeyer, L. "Ueber ein dem Aphrosiderit F. Sandbergers ähnliches Mineral. Zeits. f. Chem. und Pharm. (1860). p.145-50.

IV. "Aphrosiderite" cited by Orcel[1] (p.388); Richard, G. "Veins with fibrous quartz and chlorite from the vicinity of Providence, Rhode Island". The Amer. Min. Vol.10 (1925). pp.429-33.

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1 Orcel, M. J. "Recherches sur la Composition Chemique des Chlorites". Bull. de la Societé Francaise de Minéralogie. Vol.50 (1927). pp.75-456.

V. "Prochlorite", cited by Oreel[1] (p.334); Samoiloff: Materialen z. Miner. Russlands (1906).

VI. "Ripidolite", cited by Orcel[1] (p.357); from Batesville, Virginia.

VII. "Thuringite", cited by Hallimond[2] (p.28); Zalinski, E. R. Neues Jahrb. Min. (1904). B.Bd. 19. pp.40-84.

VIII. "Thuringite", cited by Hallimond[2] (p.28). Penfield and Sperry. Amer. Journ. Sci. (1886). Vol.32. p.307.

Since the optical properties of the authigenous chlorites in both the mudstones and the matrix of the grits are uniform and practically identical with the chlorite just investigated, it may be inferred that the chlorite of these rocks tends to the same composition and is represented by the above formula.

The sphaerodialogite band was observed on the eastern slopes of the Cwm Mynach Valley in the exposures afforded by the manganese workings. It occurred approximately half an inch below the "Bluestone Grit" horizon, and at approximately the same distance above the top of the ore as at Barmouth. Its behaviour is similar to that already described, i.e. it is folded, while immediately above and below the bedding is regular and more or less plane. The folding is not as acute, however, as at Barmouth. Also the band is not uniform in character, but develops frequent lateral passages into a thin grey-green band with a lithology similar to that described on p. above, and which contains frequent developments of the "irregular white blotchy" material.

Higher up in the succession at Barmouth, 2 ft. 3 inches above the ripple band occurs a thickness of blue-grey mudstone, several inches thick, through which is irregularly developed along bedding horizons, irregularly spherical and lenticular masses up to a quarter of an inch in thickness. These have a lithology identical with that of the sphaerodialogite band, and are similar in every way except that they are not regularly extended laterally.

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1 op cit.

2 Hallimond, A. F. "Iron Ores: Bedded ores of England and Wales. Petrography and Chemistry". Spec. Rep. on the Mineral Resources of Great Britain. Vol.XXIX. Mem. Geol. Surv. (1925).

General Petrology of the Sphaerodialogite bands.

E. Spenser's[1] work on spherulitic carbonate deposits led him to conclude that they were formed by the crystallization of the carbonate within a sediment of colloidal or semi-colloidal character. [Full discussion of the various structural features of the spherulites and their relationship to his postulated mode of origin will be found in the paper cited.]

H. Schade demonstrated that concretionary bodies result when a substance passes from the state of an emulsion colloid to that of a solid on dehydration, and that if the change leads to a crystalline state the resulting structure is radial if the substance is pure, but concentric if other substances are precipitated along with it.[2] E. Spenser in discussing the origin of the spherulitic carbonates merely postulates that the carbonate was absorbed by the "fine-grained and partly colloidal sediments, and carried down with them during deposition",[3] a suggestion which met with some opposition. Schade, as above, suggests that the materials now forming the spherulites, were themselves originally colloidal, and there seems to be some evidence for this in the present case. In the pale greenish-grey mudstone (p. 121), where it has not crystallized with the production of spherulitic structures, the carbonate presents very small globular bodies, totally devoid of crystalline shape, which are very similar to true collofomm structures. This minutely globular character of the carbonate is very typical of all these rocks and will be referred to again. In addition, the "irregular blotchy developments" which are often composed almost entirely of manganese carbonate, show the typical irregular and botryoidal shapes regarded as typical of colloidally formed materials. Many of these bands also show a well developed system of contraction cracks, which can be regarded as strong evidence in favour of a colloidal origin. In connection with this, also, it is interesting to note that Bucher[4] states that calcium carbonate is the best known of the

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1 "On some Occurrences of Spherulitic Siderite and other Carbonates in Sediments". Q.J.G.S. Vol.LXXXI (1925). p.667-703.

2 Cited by Bucher, W.H. in Journ. Geol. Vol.XXII. p.593.

3 loc. cit. p.687.

4 loc. cit. p. 597-8

gelatinous salts, and that colloidal siderite forms in bogs and stagnant seas.

If the manganese carbonate is regarded as being originally of a colloidal form as well as the accompanying alluminous gel, then there is no need to imagine the absorption of 70 - 80 per cent of carbonate in a rich sphaerocarbonate rock by 30 - 20 per cent of colloidal siliceous clay, a possibility which A. F. Hallimond doubts[1], and, in addition, the necessary condition for the formation of such spherulites, as postulated by Schade, would seem to be fulfilled.

From a colloidal mixture of manganese carbonate and clayey substances, spherulites of dialogite would form by the crystallization of the colloidal carbonate, and the radial structure would be due to the expulsion of nearly all the "impure" clayey materials. A little clayey material, amounting, at most, to one or two per cent, was occluded within the spherulite and this, in confirmation of Schade's work, gave rise to a concentric structure, superimposed upon the radially developed fibres. The occluded material was dispersed in an extremely finely divided state through the spherulite and because of this was "protected" from subsequent change, while the expelled clayey material filling the interstices between the spherulites, recrystallized as quartz and chlorite when the rock became indurated.

In the spherulitic "ripple" band, the clayey materials were merely expelled from the spherulites during crystallization. In the "irregular white blotchy developments", this expulsion was carried a stage further, the present chloritic material being concentrated in the margins of the development, while the central portion consists of massively developed spherulites without any interstitial material.

A more or less constant amount of clayey material was retained by the spherulite on crystallization, since the amount of included material in each spherulite tends to be approximately the same.

Crystallization of the carbonate to form spherulites only seems to have taken place under special circumstances, since, forinstance, in the green-grey band (p. 120) and throughout many of the normal mudstones considerable

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[1] In discussion of E. Spenser's paper, loc. cit. p.703.

carbonate material was present dispersed through clayey material, yet no spherulites have been formed. No indication of these special circumstances is forthcoming.

An original colloidal condition would also seem to explain the peculiar folded character of the sphaerodialogite band. If the band, before consolidation, consisted of two components, a gelatinous portion of aluminous and siliceous materials, and included in that, colloidal manganese carbonate, which was undergoing crystallization, then this being solid would tend to strengthen the gel and the resultant mass would have a thick dough-like consistency. A suggestion as to how this band was thrown into the overfolds described can be stated as follows. A loose sandy deposit on being subjected to wave or current action is thrown into ripple marks, and these ripple marks have a constant limiting position of stability. When a ripple mark has reached this position further current or wave action results in the movement, bodily, of the ripple mark, with constant re-sifting of the material forming it. Thus the ripple mark continually tends to maintain the same shape. If, however, the material undergoing such current or wave action had a dough-like consistency, it would be unable to re-sift its materials in order to maintain a fixed state of stability, and the effect of continued action would be an accumulative one, the ripple being thrown into exaggerated humps, finally producing overfolds, due to its inability to break down after reaching the normal position of stability. The direction in which the ripple marks are overfolded gives the direction in which the current is operating. In the case of the sphaerodialogite band ~~of A,~~ this was towards E 6°N.

THE MANGANESE ORE.

The Manganese Ore.

Petrography.

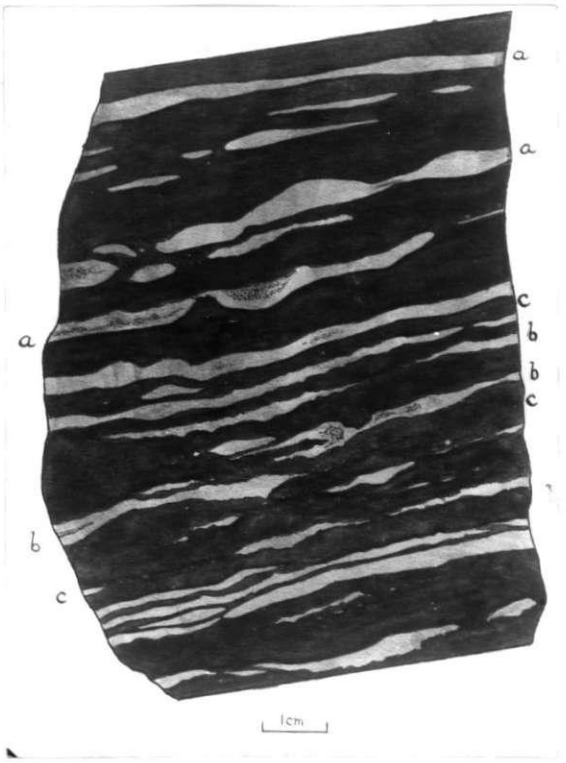
I. Macroscopic Characters.

Considered as a whole, the manganese ore-rock is extremely fine-grained, compact and chert-like in appearances, no individual grains being discernible with a lens. It is very hard (hardness approximately 6.5), all the varieties having a more or less equal hardness. The fracture is uneven and almost conchoidal. The rock is totally unaffected by cleavage, but is frequently traversed by an irregular rectangular jointing, the joints being often infilled by vein quartz. In addition fairly common quartz veinlets traverse it irregularly in a vertical direction. These vary in width from less than a mille metre to several millimetres. On treatment of the rock with 1:1 hydrochloric acid there is effervescence of carbon dioxide.

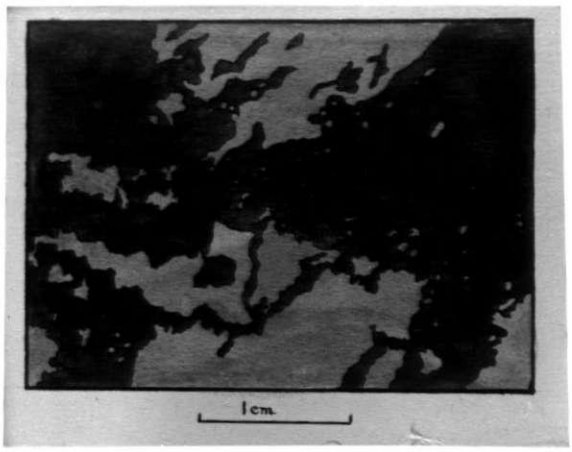
The ore is typically exposed in the Barmouth district. It consists, predominantly of a regular alteration of chocolate-red and yellow bands. Bands of a chocolate-purple colour are modifications of the paler chocolate-red type, and paler, cream bands are modifications of the true yellow bands. In addition layers of a dark bluish-black colour occur occasionally.

With regard to the main type, the chocolate-red material is by far the most abundant and most regularly developed portion of the rock. Throughout this is distributed, at more or less regular intervals, bands of the yellow material. These differ from the former in being thinner, and whereas their bedding is regular, each bed when traced laterally, is found to behave in an irregular manner. In thickness, the yellow bands vary between 1.5 mm. and 3 mm. and are rarely 6 mm. The distance between successive yellow bands, i.e. the apparent thickness of the intervening chocolate-red bands varies between 3 and 10 mm. Thus when the rock consists wholly of alternations of red and yellow material, the red portion forms three-quarters or more of the rock.

The yellow bands vary in thickness when traced laterally. This variation is sometimes gradual and sometimes abrupt so that lenticular masses occur. The layers are very frequently impersistent, but nearly always the individual portions of the layer terminate with quite blunt and rounded ends. Sometimes the yellow bands are relatively continuous, individual layers being traceable for several feet - but this is rare. More often they persist for a few inches only. When a layer is impersistent, distances varying from fractions of an inch to one or two inches may separate the various portions of the same layer. Occasionally, a yellow layer is represented by a series of



A



B

Fig. 25 The Manganese ore: workings near Cell Fechan Farm, 1/2 ml. N.E. of Barmouth.

The normal ore, consisting essentially of a regular alternation of chocolate-red and yellow bands:

A. Vertical section: (a) regular yellow bands, with smooth upper and lower surfaces; n.b. the blunt endings of individual portions of the same layer, (b)yellow layers with irregularly corrugated upper and lower surfaces, (c) lines of spheroidal globules of yellow material in the spaces between isolated portions of a discontinuous yellow band.

B. Section parallel to the bedding. Note the very irregular outline of the separated portions of yellow material and the globular bodies which occur between them.

small lenticular developments, upto 10 or 15 mms. long, separated by varying distances, and somewhat rare isolated lenticles are observed which appear to have no lateral equivalents. The vertical distribution of these yellow bands through the chocolate-red material is not regular: frequently several of these yellow bands quickly succeed one another with only small thickness of intervening red material, and again, sometimes only three or four layers of this yellow material may occur interspersed through several inches of rock. Rarely the yellow bands may have irregularities in the vertical plane, e.g. minor flexures, which are obviously contemporaneous in origin, since they are not repeated in the bands immediately above and below. The upper and lower surfaces of the yellow bands are usually very smooth and regular (apart from the gentle undulations caused by the thickening and thinning of the band), e.g. Fig. 25 a, but they may sometimes be uneven and irregularly corrugated (such bands are seen in Fig. 25 b). If the surface of such a layer be cut parallel to the bedding, a very irregular outline with inlays of the chocolate-red material is seen (Fig. 25 B). A noteworthy fact is that both surfaces of a yellow band tend to have the same characters, i.e. they are either both smooth, with the gentle undulation tending to be reflected vertically, or they are both irregular.

At times, when a yellow band is divided, the spaces between the individual portions of the yellow material contain a thin line of small globular developments (of the same material) at the level of the band. These are usually up to 1 mm. in diameter and are approximately sphaeroidal in form, that is, they have the form of a sphere which has been flattened parallel to the bedding. These spheroidal bodies decrease in number away from the main developments of the yellow material - a feature well seen in Fig. 25 B. In Fig. 25 A these developments are clearly perceptible in the bands marked c.

When a yellow band, consisting of many laterally separated portions is cut parallel to the bedding, the petering out is approximately equal in all directions so that the individual portions of the layer are each equidimensional in the plane of the bedding (Fig. 25 B). The outline of each of these isolated portions is extremely irregular, and frequently they are surrounded by a zone in which the small spheroidal masses (having circular outline in this section) are developed. These are approximately a millimetre or less in diameter.

The bedding of the chocolate-red material is much more uniform

than that of the yellow material, and is invariably continuous laterally. Where the yellow bands peter out, the red layers merge completely with one another, no line of contact being seen. Often, with the aid of a lens, the red portion of the rock is seen to consist of a regular succession of laminary developments, fractions of a millimetre in thickness, the alternate layers being of the true chocolate-red type separated by paler material approximating in character to the material of the normal yellow bands. These laminae appear to be perfectly continuous laterally and they follow regularly the contour of the red band itself. They are not always discernible, many red layers occurring which are not apparently so constituted.

Compensation for the variations in thickness, the lateral disappearance, minor flexures etc., which occur in the yellow bands, is secured by the opposite adjustments in the red layers, equal adjustment taking effect both above and below the yellow band. The result of this is the appearance of very regular bedding.

The junctions between the chocolate-red layers and the true yellow bands are abrupt and there is no transition of one into the other.

The chocolate-purple material is merely a more deeply coloured modification of the chocolate-red type and has the same characteristics.

Normally when these regularly bedded yellow and chocolate-red materials are developed in the manner just described, intercalations of cream or bluish-black materials are very rare. In portions of the ore, however, the cream material is especially abundant. This is especially common in the outcrops on the western side of Mynydd Cwm Mynach. Here the cream has almost entirely taken the place of the normal yellow material; and it is often relatively very abundant, forming one third to one half of the total volume of the rock. It has the same irregular characters as the true yellow type, but its greater abundance, and its badly defined junctions with the chocolate-red material, cause the rock to appear far less well banded than normally. The cream material appears to merge into the red, which often in these associations is much paler in colour than usual, and layers occur which are intermediate in character between the cream and red. The individual cream coloured layers are thicker on the whole than were the true yellow bands, but they still vary in thickness laterally, although the actual petering out of the bands is not so evident. In these cases the chocolate-red layers are again much more regular than the cream, though since they merge into the latter they are not as regular as in the normal yellow-chocolate red

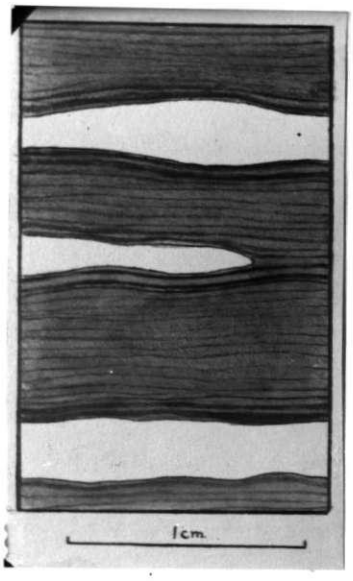


Fig.26 The manganese ore: workings near Cell Fechan Farm, 1/2 ml. N.E. of Barmouth.

Showing the laminated character of the chocolate-red material.

associations.

The dark bluish-black material is not very abundant in the Barmouth locality. It is quite important in the Diphwys region, and is relatively abundant in the Moelfre and Rhinog Fach-Y Llethr localities. In the Cwm Mynach region it occurs in association with the cream developments. In the main it appears to be a modification of the chocolate-red type, though some bands show affinities to the yellow material. Sometimes the blue-black colour is accompanied by a purplish tinge indicating an association with the chocolate-red material. The bands are relatively irregular in their development and they frequently pass laterally into material of the chocolate-red type and occasionally into the yellow. Sometimes the upper and lower margins of the layers are clearly marked; at others both margins are badly defined, while occasionally the lower margin is badly defined and the upper sharply demarcated, or vice versa. Frequently the central portion of a band of blackish material shows a distinct purplish tinge. These blackish bands tend to a thickness of 5-10 mm.

Many of the structures of the rock are seen more clearly by examining the thin section, or a polished surface with little or no magnification.

(a) <u>The regularly laminated character of the chocolate-red material.</u> In thin section (in ordinary light without magnification) the chocolate-red material is seen to consist of a regular alternation of thin laminae of a reddish-brown colour with others which are practically colourless. These layers vary in thickness from about 0.1 mm. to about 1.0 mm. Considering an individual chocolate-red band bounded above and below by well developed yellow material, the general tendency is for the intensity of colour and abundance of the reddish laminae to be much better developed in the upper and lower portions of the band (i.e. in the portions adjacent to the yellow bands) while in the middle portion of the band the individual laminae are not so distinctly marked and they tend to be further apart. The colourless and reddish laminae are not clearly marked off from one another; they merge imperceptibly, a character best observed under the lower powers of the microscope. When thus examined the reddish laminae are seen to contain colourless material, and the colourless laminae reddish material scattered thinly throughout. Both types of laminae consist of the same

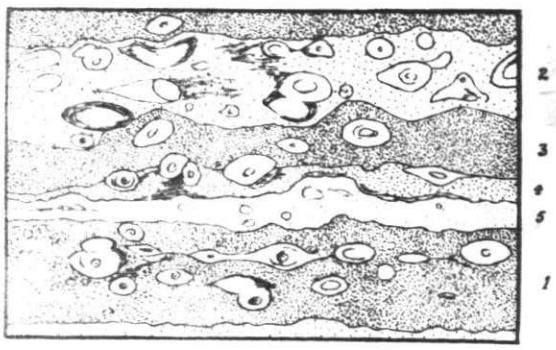


Fig. 27 Spheroidal bodies in manganese ore; S.W. slopes of Rhinog Fach.

1. Spheroids of normal yellow colour in chocolate-red material.

2. Spheroids in normal yellow band.

3. White spheroids in chocolate-red material.

4. Very pale chocolate-red band with yellowish spheroids.

5. Normal yellow material with very ill-developed spheroids.
Magnification x 3.

two compenents, the "red" ones containing a marked preponderance of red over colourless material and the "colourless" ones of colourless over red. A feature of these laminae is their lateral persistence and they show no characteristics/ irregularities. The lamination of the chocolate-red bands is perfectly regular until some major irregularity is encountered within the chocolate-red band itself when the laminae may in part cease or new ones come in. The individual laminae tend to be congruent with the upper and lower boundaries of the band; the undulations in the surface of the band, caused by thickening, thinning, and lenticular developments in yellow bands, are repeated in the laminae, the undulations gradually dying away towards the middle of the band. Thus the middle laminae always tend to a much greater regularity of behaviour, merely following the major undulations of the chocolate-red bands.

Occasionally laminae of equal strength are developed throughout the band, and sometimes a well marked lamina may occur in the middle portion of the band.

(b) The development of small spheroidal bodies with a concentric structure. Small spheroidal bodies of ore material occurring irregularly scattered through normal mudstone were described in the section on mudstones (pp. 58).

Within the ore itself these spheroidal bodies are usually of yellow material. They are often developed in the space intervening between two isolated portions of a discontinuous layer of yellow material. They tend to be more closely packed the nearer they are to the larger masses of yellow material. In size they vary from 0.90 mm. to 1.55 mm. in horizontal diameter and from 0.65 mm. to 0.75 mm. in vertical diameter (see Fig. 27).

Within the ore on Diphwys and Rhinog Fach spheroidal bodies of yellow material occur scattered throughout chocolate-red material when comparatively continuous layers of the yellow type are not present. In these cases it is practically always seen that these spheroids are arranged in definite layers parallel to the bedding of the rock. These spheroids, which have no immediate connexion with more continuous layers of yellow material, are nearly always larger in size than those described above: frequently from 4-6 mm. in maximum diameter.

Similar spheroidal bodies of yellow material are developed within some of the yellow layers themselves. When the yellow bands have smooth

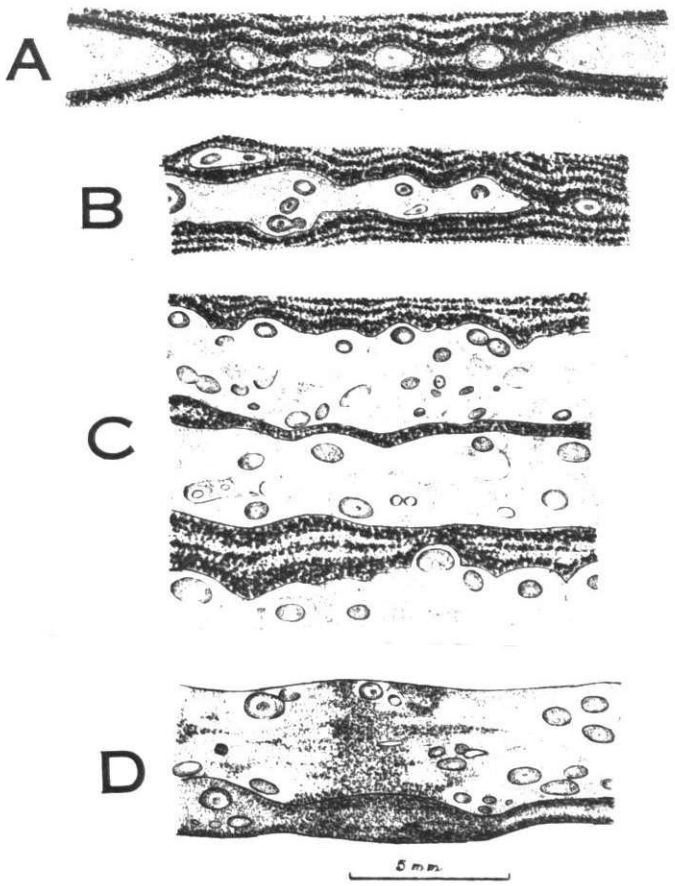


Fig. 28 The Manganese ore; workings near Cell Fechan Farm; 1/2 ml. N.E. of Barmouth.

The development of spheroidal globules of yellow material within the ore:

A. Spheroidal bodies, surrounded by normal chocolate-red material connecting two portions of a discontinuous yellow band.

B. Developed within normal yellow material and being directly responsible for the corrugated surfaces of the band.

C. In pale cream material, with haloes of practically colourless material surrounding the spheroids.

D. Development within a black band, which itself has affinities to yellow material.

upper and lower surfaces (e.g. fig 25A.a) they do not usually occur. When, however, the bands have irregularly corrugated surfaces (e.g. Fig. 25A.b) they are usually abundant and account in themselves for the irregularities in the surfaces of the band. The flattening of the bodies is again parallel to the bedding and they vary in size from 0.75 mm. to 2.5 mm. They are seen to be irregularly scattered throughout the band, being present especially in the upper and lower portions, the middle portion being relatively free from them. (Fig. 28B). They are freqently developed within the paler cream bands of the ore (Fig. 28C) and they are also quite often seen in bands which have affinities to the yellow material, but which contain a fair amount of disseminated pyrolusite, which gives them a bluish-black colour (Fig. 28D). In this case the spheroids themselves are free from black material, which is often concentrated in a zone immediately surrounding the spheroid.

Sometimes, e.g. in the ore from Rhinog Fach spheroidal bodies are developed with bands having a more or less purple colour: these differ from the normal spheroids in being white with a faint purplish tinge, often arranged in concentric bands.

Structually all the spheroidal masses are similar. They possess an indifferently to well developed concentric structure, radial characters being entirely absent. The number of concentric zones is usually two or three. Usually the outer zone is of a more deeply coloured yellow material, which is succeeded inwards by a paler, almost colourless zone, (which, if only two zones are present, forms the central portion of the body). When three zones are present the central zone succeeding the colourless zone is of material similar to that forming the outermost zone. When the spheroids are embedded in chocolate-red material, the passage from the red to the yellow material of the spheroid is very sharply demarcated. When they are developed within bands of yellow material they are not so clearly marked. The matrix material immediately surrounding them is of a paler colour than the outermost zone of the spheroid and the passage of this pale material into the spheroid is not very well marked, while its passage into the normal yellow matrix is very gradual.

(c) <u>Contraction cracks</u> (see Fig. 29). These are best examined under a lens or the lower powers of the microscope. They take the form of narrow veinlets traversing the bands approximately at right angles to the bedding. They develop rather differently in different portions of

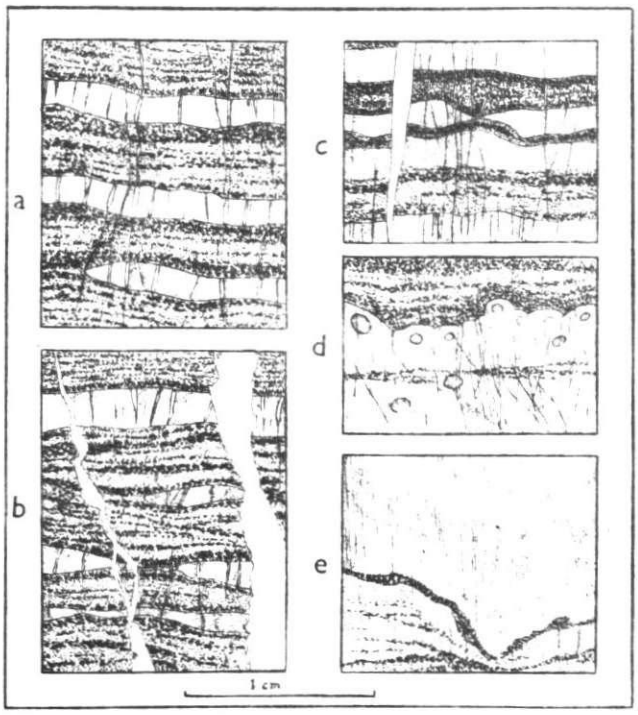


Fig. 29 The manganese ore; workings near Cell Fechan Farm, 1/2 ml. N.E. of Barmouth.

The contraction cracks, which appear as small infilled veinlets aligned approximately at right angles to the bedding.

(a) showing development in ore consisting of normal alternations of chocolate-red and yellow materials;

(b) the same, to show the difference between the contraction cracks and ordinary veins;

(c) narrow veinlets with good development in the red as well as in the yellow material;

(d) showing relationships of contraction veinlets to the spheroidal bodies developed with bands of yellow material;

(e) veinlets developed within cream material.

the rock.

In rock exhibiting the normal alternation of chocolate-red and yellow materials, the veinlets are more abundantly developed in the yellow bands (Fig.29a). Less than 50 p.c. of the veinlets traversing the yellow bands penetrate the adjoining red material. These veinlets which are confined to the yellow material peter out absuptly and rarely extend beyond the junction of the two layers. The few veinlets which do continue into the chocolate-red material undergo a sudden decrease in width on passing from the yellow into the red material. It is the more robust of the veinlets within the yellow material which continue into the chocolate-red. The veinlets confined to the yellow material vary from 0.02 mm. to 0.12 mm. in width, averaging 0.05 mm. The others vary from 0.10 mm. to 0.20 mm. within the yellow band itself and their continuations into the chocolate-red material from 0.02 mm. to 0.12 mm. Often a veinlet which is well developed in the yellow material becomes discontinuous and irregular on entering the chocolate-red material, into which it fails to penetrate very far. The veinlets are clearly marked off from the rock itself and the junctions are sharp. They tend to occur at right angles to the bedding and are all roughly parallel; at times they are inclined slightly, but even then parallelism is evident. Each veinlet is complete within itself and there is little or no tendency for the veinlets to branch. The walls of the veinlet are parallel and have approximately plane surfaces. Thus they exhibit a sharp contrast to the irregular junctions and frequent branching etc. of ordinary quartz veining (see Fig.29b). The veinlets are infilled by secondary (chalcedonic) silica, and for (especially in the case of the narrower veinlets) very fine grained granular dialogite, or, more rarely, crystaline dialogite showing good rhombohedral outlines, especially when set in quartz.

Occasionally similar contraction cracks are observed crossing the rock with no marked increase in development within the yellow material, e.g. Fig.29c . Such cases, however, are not abundant. In character they are similar to those described above.

The relatively thick yellowish bands developing abundant spheroidal bodies (e.g. Fig. 28c) are traversed by very numerous narrow veinlets 0.02 mm. to 0.06 mm. in width (Fig. 29 d). They again tend to be at right angles to the bedding, but more frequent deviation up to 25° are

seen. Again each veinlet is complete within itself and there is no tendency for branching. When two veinlets, having different inclinations, meet, they pass through one another without any variation in direction or size due to mutual interference. These narrow veinlets are composed almost invariably of fine grained dialogite, the thicker only sometimes developing silica locally in the central portions. Again only the better developed of these veinlets pass beyond the limits of the yellow material into the chocolate-red. The veinlets traverse the spheroidal bodies without break or variation in thickness ; they were thus formed when the spheroidal bodies were already in existence.

In the more massive cream-coloured bands, the veinlets are similar to those described in the above paragraph, but they are much more abundantly developed, and are often narrower (Fig.29e). They tend more or less to one direction, which despite the frequently irregular nature of the bands themselves, is constantly at right angles to the major bedding plane, i.e. the original bedding surface. They are almost entirely composed of fine grained carbonate and stand out very clearly between crossed nicols. In spite of their very narrow character, their junctions with the rock itself are very distinctly marked. They again suffer a great decrease in number on crossing into the red material and they again traverse, in an undisturbed manner all the internal structures and variations within the yellow band. This shows that the internal heterogeneous character of these cream bands originated before the contraction cracks.

Veinlets traversing the blackish bands have the same characters and are fairly numerous. They are very narrow and almost entirely filled with dialogite.

These veinlets cause no vertical displacement whatsoever of the structures on either side.

In addition to these veinlets another group of veins traverses the ore. They are obviously the normal veins of tectonic origin. They are frequently from 0.5 mm. to 5 mm. in width but merge by transition through all sizes into the large scale regional veining. They are usually very irregular in character, branching and merging one into another; their walls, though clearly defined have very irregular surfaces. There is no marked parallelism of adjacent veins and they often cause slight vertical displacement. They are filled chiefly with quartz, the smaller ones through the ore containing crystalline dialogite, with minor developments

of iron ores, chlorite, rare tourmaline and garnet.

The reasons for regarding the veinlets described above ~~are~~ as infilled contraction cracks due, to the drying of the colloidal rock material prior to consolidation may be summarized as follows:-

1. Their greater development in the yellow as compared with the chocolate-red material.
2. The fact that many of the veinlets developed in the yellow material peter out abruptly at the junction with the reddish material, and are not carried beyond.
3. The sudden thinning of the veinlets which are continued into the reddish material, immediately on crossing the plane of junction from the yellow material.
4. Their plane character, together with the parallelism of their walls.
5. Their arrangement at right angles to the bedding planes.
6. The marked parallelism of the veinlets viewed as a whole.
7. The nature of the infilling material: composed almost entirely of fine grained dialogite similar to that forming the rock itself (and obviously the veinlets were filled while the same sourse was available), and only rare chalcedonic silica.
8. The size of the veinlets: the limits of variation are small, and viewed as a whole they are of a uniformly small size.

II. The Mineralogical Composition of the Manganese Ore.

(a) The chocolate-red material[1]: This consists of a very fine grained intergrown mosaic of dialogite, colourless to pale yellow spessartite garnet, and silica, in addition to which reddish-brown garnets are usually developed on a very minor scale. The dialogite and the colourless garnet form by far the bulk of the rock (approximately 90 p.c. +). The garnets are small and have enhedral six-sided outlines; they vary in size from 0.004 mm. to 0.018 mm., being on an average about 0.014 mm. Micrometric analysis indicates that they form 50-55 p.c. of rock. In section they are seldom isotropic, since owing to their size in individuals do not extend through the entire thickness of the section. Occasionally small localized areas of an almost isotropic character are observed: these areas must be composed almost entirely of the garnet, so that a more or less compact aggregate of these small crystals extends through the thickness of the section. Sometimes good isolated garnets are observed on the margins of the slice and these are truly isotropic. The garnets are best examined by crushing the rock and treating the powder, after passing it through a very fine-meshed seive, with warm hydrochloric acid. The insoluble residue which consists chiefly of garnet with some quartz is then mounted in the ordinary way. The garnets so obtained are small, equidimensional, and frequently show good six-sided outlined, suggestive of the rhombicdodecahedron. These good isolated crystals are always isotropic. Some of them are water clear but the majority of them contain very minute reddish-brown inclusions; these vary from a few to dense aggregates or clouds. They are usually concentrated in the central portion of the crystal, but the cloudy masses frequently extend to quite near the margins. From the computed analyses of the insoluble residue (see pp. 146ff) these small inclusions are regarded as being haematite, as there is excess ferric iron present over the amount necessary to enter into the composition of the garnet. The garnets are set more or less regularly throughout the dialogite matrix.

The dialogite is colourless and has a refractive index varying approximately from 1.60 to 1.80 . The birefringence is extreme, (greater than that of calcite) and is approximately equal to 0.20-0.25. It is entirely devoid of any true crystal form and frequently in section appears

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[1] All varities of the ore material on account of their extreme fineness p of grain are best examined under the 1/2 inch oil immersion objective.

to exist in small granular globules up to 0.040 mm., a character best observed between crossed nicols. When examined in powder form the individual fragments are irregular in shape and only very rarely suggest such crystalline characters as rhombohedral cleavage. The mineral is clear and does not contain any of the reddish-brown inclusions characteristic of the spessartite.

The reddish-brown garnets are apparently similar to those occurring in the mudstones and grits, but in this case there is a marked absence of euhedralism. They occur as small irregular granules scattered irregularly and thinly throughout the section and are approximately equal in size to the colourless garnets. The chocolate-red bands which are deepest in colour contain a greater proportion of these reddish-brown garnets. When examined in the rock powder they are seen often to contain minute inclusions similar to those of the colourless garnets.

The silica is not abundant; it is water-clear and has an interstitial relationship to the other constituents. It stands out by virtue of its relatively slow refractive index, but it is best seen under crossed nicols when it presents low first order polarization colours in contrast to the high order colours of the carbonate.

The laminated character of the chocolate-red bands, described previously, is seen also under the high powers of the microscope. The colourless laminae consist almost entirely of dialogite, spessartite (almost exclusively colourless), and quartz. The reddish laminae differ in that while composed of the same materials in a similar manner, dispersed throughout are cloudy masses of a reddish-brown colour, to which the colouring of the chocolate-red material is obviously due. This cloudy reddish-brown effect is the result of the aggregation of the minute spessartite garnets, each of which contains clouds of inclusions of reddish-brown material (as described above). The garnets, therefore, of the reddish laminae contain abundant inclusions of haematite, while the garnets of the colourless laminae are practically free from them. This present segregation of the haematite into laminae within the chocolate-red material apparently represents an original difference in the distribution of the iron through the bands. This, on formation of the minute garnets, was taken up, in situ, to form inclusions of haematite.

(b) <u>The normal yellow bands</u>: These have a more compact appearance. They

consist of a very fine-grained intergrowth of dialogite and spessartite garnet, identical with those described from the chocolate-red layer. There is a complete absence of the cloudy reddish-yellow material which gave the colour to the chocolate-red layers, and the reddish-brown garnets are practically absent. Locally scattered throughout is an indefinite yellowish mineral of low refraction, which is possibly an aluminium silicate. The character under crossed nicols is governed by the disseminated dialogite, though small areas of semi-isotropic character occur scattered locally throughout. The quartz is again interstitial, but is, relatively, not so well developed as in the chocolate-red bands.

The junction between the chocolate-red bands and the yellow bands is clearly demarcated even under the higher powers of the microscope and there is no zone of transition one into the other.

(c) The paler cream-yellow bands: These are mainly dialogite with fewer garnets. In section (especially between crossed nicols) they have a more uniform appearance and no rhombohedral crystalline characters are definable. Apart from the greater proportion of carbonate and an absence of the yellowish, possibly aluminous material, the characters are the same as in the normal yellow material. Reddish-brown garnets are again practically absent and there are no cloudy masses of minute inclusions. Locally developed within these cream-coloured bands are irregular patches of the normal yellow material.

(d) The bluish-black layers: These consist of a fine-grained intergrowth of dialogite and spessartite, as described above, throughout which is scattered small indefinitely shaped grains of a black opaque material, found by chemical analysis to be pyrolusite. It varies in concentration throughout the bands, and there is a distinct tendency for it to be concentrated in layers parallel to the bedding, which are of a similar nature to the alternating reddish and colourless laminae of the normal chocolate-red material, and it is obviously a related phenomenon. This is seen very clearly in specimens obtained from the Diphwys Mines. The grains vary in size from 0.002 mm. to 0.020 mm., and they form from 2 to 5 p.c. of the bands.

The formation of the pyrolusite within these bands is regarded as being primary and not due to selective oxidation of the dialogite. This is clearly demonstrated by the fact that when these bands are traversed by cracks along which secondary oxidation of the carbonate, due to weathering

has taken place, the weathered portion is of a dense black nature, and not merely speckled with irregular grains of pyrolusite. Weathering progresses slowly with the total obliteration of the carbonate, and not with sporadic and partial alteration of dialogite to oxide. The junction between the weathered rock and the non-oxidized portion is very sharply marked, and there is no transition from totally oxidized rock through partly oxidized rock to unaltered rock. Therefore in a band containing, say, 5 p.c. of disseminated pyrolusite and 50 p.c. of dialogite, the pyrolusite could not be due to only partial and selective alteration of dialogite, which is homogeneous in character throughout.

(e) The spheroidal bodies of yellow material.

(1) The isolated spheroids enclosed in chocolate-red material, (as in Fig.28A). These are before described have a concentric structure, with two or three concentric zones to each spheroidal body. There is usually a more deeply marked, cloudy, yellowish outer rim, succeeded by a clear colourless zone, often succeeded by a third and central zone of material similar to the outer zone. Often this third central zone appears to be absent when the section is not medial. The darker yellowish zones consist of dialogite and spessartite and the yellowish (aluminous (?)) mineral, while the colourless intermediate areas consist predominantly of dialogite. The textures of both are similar to each other and to that described for the yellowish material proper. The outer and central areas of yellowish material are similar to the normal yellow ore, with, if anything, a greater development of the yellow mineral and the spessartite. The greater development of spessartite is noted by frequent occurrence of semi-isotropic areas, as distinct from the colourless zones which possess no tendency to isotropy whatsoever. This isotropic effect is often more noticeable in the central area, a large proportion of this area is often completely isotropic.

(2) The spheroidal bodies developed within the yellow bands: The spheroidal bodies themselves are similar to those just described, i.e. they are concentric structures, with outer and inner zones of a yellowish colour and an intermediate zone practically colourless, and the amount of spessartite is again noticeably greater in the yellow zones than inthe colourless zone.

When developed in the normal yellow material, some of the spheroids are distinguished with difficulty from the matrix, in which they are set (Fig.28C) the external yellowish zone merging completely with the normal yellowish material. Thus the spheroids are not abruptly marked off from the

material in which they are set as was the case of spheroids set in chocolate-red material. In this case, the colourless zone of the spheroid, which is usually clearly marked is separated from the normal yellow material of the band by a zone of material which blends on the outside with the matrix and is of a brighter yellow colour than the matrix material itself. This brighter yellow material apparently contains more spessartite.

Frequently (Fig. 28c.) when the spheroids are developed in the paler cream material, they are surrounded by a comparatively wide zone of colourless, dialogite-rich matrix material, thus showing that the spheroid was formed by the draining towards a central point of the aluminous materials from over a relatively large area. The surrounding colourless area merges gradually outwards into the normal pale yellow material. Frequently when the spheroidal bodies are abundantly developed, the areas of colourless material surrounding them are continuous, and in the matrix surrounding the spheroids there may be but little true yellow material at all.

(3) Spheroidal bodies developed within bluish-black bands: These again show the same two- or three-zone concentric structure. They are developed in a matrix, throughout which are scattered fairly abundant small grains of pyrolusite. The spheroids themselves are frequently surrounded by a concentric zone (which merges gradually with the matrix) in which the small grains of pyrolusite are more abundant than they are in the matrix. The spheroids themselves have no included pyrolusite and this concentration of pyrolusite in the zone surrounding them indicates that it was all expelled as the spheroids formed.

(f) Contraction cracks: These are usually filled with dialogite of a very fine grained crypto-crystalline variety, which bears a distinct similarity to that of the ore rock itself, thus indicating a similar and pene-contemporaneous source. Frequently the wider cracks, e.g. these occurring in some of the normal yellow bands, contain both dialogite and silica. The silica is chalcedonic, the fibres being orientated at right angles to the veinlet walls. The silica usually occupies the central portion of the veinlet. Sometimes minute colourless garnet are distinguished identical with those of the ore. Good rhombohedral crystals of dialogite occur, rarely within the chalcedonic silica.

In certain rare instances irregular patches of a brown colour are developed. These are fine-grained and relatively soft. Under the microscope they are seen to consist of a fairly bright yellow mineral

interspersed in a matrix of dialogite with relatively rare spessartite. The crystals of the yellow mineral are usually very small and intergrown. Occasional larger moderately well developed crystals intergrown with the earthy aggregate show a good longitudinal cleavage, with a parallel extinction. The refractive index is greater than that of Canada balsam, but less than the average refractive index of the dialogite. Polarization colours are completely masked by the original colour of the mineral, but rare crystals show up to first order blues. The mineral is feebly pleochroic from nearly colourless to bright yellow with maximum absorbtion parallel to the cleavage traces.

This material was analysed and its chemical composition calculated* (see pp. 159-61).

III. The Chemistry of the Ore Materials.

I. Analysis of a "mixed" portion of ore material, i.e. containing red and yellow developments; S.W. slopes of Rhinog Fach.

Insoluble Residue	50.94	SiO_2	27.17	53.34
		Al_2O_3	7.07	13.89
		Fe_2O_3	1.38	2.71
		FeO	1.17	2.31
		MnO	13.88	27.24
		MgO	0.12	0.24
		CaO	0.46	0.91
			51.25	100.64

Al_2O_3	1.30
Fe_2O_3	1.75
MnO	22.96
MgO	1.28
CaO	5.08
Na_2O, K_2O	negligible
	16.87
CO_2	100.18

Specific Gravity estimated by Pycnometer method = 3.61.

The insoluble residue is composed of spessartite garnet and quartz, while the soluble portion consists of dialogite containing in addition to MnO, small quantities of FeO, MgO, and CaO.

To find specific gravity of insoluble residue:

The rock contains:

9.07 p.c.	Calcium carbonate (sp. g. = 2.71)	= 24.59
2.68 p.c.	Magnesium carbonate (sp.g = 3.06)	= 8.17
2.54 p.c.	Iron carbonate (sp. g. = 3.86)	= 9.80
37.50 p.c.	Manganese carbonate (sp.g = 3.45)	= 129.30
		171.86

$$\therefore \text{sp.g. of Insoluble Residue} = \frac{361.00 - 171.86}{50.94}$$

$$= 3,72$$

The amount of quartz present in the insoluble residue was estimated by use of the S. J. Shand micrometer, in a mounted sample of powdered insoluble residue.

Three large counts gave 27.29, 27.56 and 28.89 p.c. by volume of quartz, giving an average of 27.91 p.c.

Using this the approximate specific gravity of the spessartite present in the insoluble residue can be calculated:

Let weight of insoluble residue = 372

then weight of quartz is $27.91 \times 2.65 = 73.96$

$\therefore$ weight of spessartite = 372 - 73.96 = 298.04

$\therefore$ Specific gravity of spessartite = 298.04/72.09

$= \underline{4.135}$

This is a good figure for the specific gravity of spessartite.

In the analysis of the insoluble residue of the rock, elimination of the excess silica will give the chemical composition of the spessartite. The amount of silica present in ideal spessartite is 36.40 p.c.

Recalculation of the analysis gives the following composition for the spessartite:

SiO_2	36.40			
MnO	36.62			Ideal Spessartite
FeO	3.11	RO = 41.29	SiO_2	36.40
CaO	1.23		Al_2O_3	20.60
MgO	0.33		MnO	43.00
Al_2O_3	18.67	R_2O_3 = 22.31		100.00
Fe_2O_3	3.64			
	100.00			

To give the RO : R_2O_3 ratio = 43.0 : 20.6 the amount of R_2O_3 in the above analysis should be 19.78 p.c. This gives an excess of 2.53 p.c. of R_2O_3 which represents excess Fe_2O_3 as the haematite inclusions of the spessartite.

By calculating the amounts of SiO_2 and Al_2O_3 required to satisfy the amounts of FeO, MgO, CaO and MnO, taken from the analysis of the insoluble portion, the following tabular representation of the composition of the spessartite is obtained:

	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	FeO	CaO	Total
Spessartite	31.92	18.05		37.71				87.68
Almandite	2.67	1.49				3.20		7.36
Andradite	1.36		1.21				1.26	3.83
Pyrope	0.50	0.29			0.34			1.13
Total	36.45	19.83	1.21	37.71	0.34	3.20	1.26	100.00

Recalculating the composition of the soluble portion, the dialogite gives the following:

MnO	48.76
MgO	2.72
CaO	10.79
FeO	3.36
CO_2	34.37
	100.00

II. The Chocolate-red Material.

Specimens were chosen where the red material was developed on a sufficiently large scale to render its separation from other materials relatively easy.

	(i)			(ii)		
	Complete analysis	Analysis of insoluble residue	Analysis of soluble portion	Complete analysis	Analysis of insoluble residue	Analysis of soluble portion
SiO_2	23.41	46.65	-	24.34	41.73	nil
Al_2O_3	9.37	17.45	1.26	11.37	17.96	2.20
Fe_2O_3	1.16	2.77	-	8.15	2.92	12.96
FeO	4.18	1.60	6.76		1.59	
MnO	37.89	29.75	46.16	38.91	34.37	45.22
MgO	0.98	0.13	1.83	0.96	trace	2.30
CaO	5.69	2.14	9.24	5.69	1.85	6.24
Na_2OK_2O	-	-	-	negl.	nil	-
H_2O+	-	-	-	-	-	-
H_2O-	0.13	-	-	-	-	-
CO_2	17.11	-	34.22	12.91	nil	30.86
	99.92	100.49	99.47	100.33	100.42	99.78
Insoluble Residue	50.07			58.18		

iii

	Complete analysis	Insoluble residue	Soluble portion
SiO_2	23.75	43.22	nil
Al_2O_3	11.01	17.14	3.97
Fe_2O_3	2.88	3.40	2.28
FeO	3.49	0.82	6.55
MnO	38.56	32.66	45.32
MgO	0.65	negl.	1.39
CaO	4.95	2.49	7.78
H_2O+	nil	nil	nil
Na_2OK_2O	negl.	-	-
CO_2	15.18	nil	32.60
	100.47	99.73	99.89
Insoluble residue	53.45		

(i) Chocolate-red material: Hendre Mines, N.W. slopes of Moelfre.
(ii) " " " Diphwys ore, E. slopes of Diphwys.
(iii) " " " East side of Cwm Mynach Valley.

The percentages of Al_2O_3 and SiO_2 required to combine with the amounts of MnO and FeO present to form spessartite and almandite respectively, were calculated. The residue of Al_2O_3 was taken to combine with CaO to form grossularite, the amount of CaO left over combining with Fe_2O_3 to form andradite. The excess of Fe_2O_3 over this amount represents free haematite in the form of inclusions. The excess of silica over the amounts necessary to combine with the bases was taken as free silica. In (i) MgO present was calculated as pyrope and in this case the andradite was neglected:

(i)

	SiO_2	Al_2O_3	MnO	CaO	FeO	MgO	Total
Spessartite	31.87	18.03	37.64				87.54
Grossularite	2.90	1.63		2.71			7.24
Almandite	1.70	0.96			2.02		4.68
Pyrope	0.24	0.14				0.16	0.54
Total	36.71	20.76	37.64	2.71	2.02	0.16	100.00

(ii)

	SiO_2	Al_2O_3	Fe_2O_3	MnO	FeO	CaO	Total
Spessartite	32.78	18.55		38.72			90.05
Almandite	1.50	0.84			1.79		4.13
Grossularite	1.46	0.83				1.37	3.66
Andradite	0.77		0.68			0.71	2.16
Total	36.51	20.22	0.68	38.72	1.79	2.08	100.00

(iii)

	SiO_2	Al_2O_3	Fe_2O_3	MnO	FeO	CaO	Total
Spessartite	32.62	18.47		38.53			89.62
Almandite	0.81	0.46			0.97		2.24
Grossularite	2.29	1.30				2.15	5.74
Andradite	0.85		0.76			0.79	2.40
Total	36.57	20.23	0.76	38.53	0.97	2.94	100.00

Thus in the analyses of the insoluble residues, there is both excess SiO_2 and excess Fe_2O_3 over the amounts necessary to enter into the composition of the spessartite. These amounts are (in terms of the total analysis of the insoluble residue):

(i) 17.63 p.c. SiO_2 and 2.77 p.c. Fe_2O_3

(ii) 9.15 p.c. SiO_2 and 2.31 p.c. Fe_2O_3.

(iii) 12.22 p.c. SiO_2 and 2.76 p.c. Fe_2O_3.

The mineral composition of the whole rock is computed to be as follows:

	(i)	(ii)	(iii)
Carbonate	49.91	41.99	46.80
Spessartite	39.87	51.36	45.23
Free silica	8.83	5.31	6.50
Haematite Inclusions	1.39	1.34	1.47
	100.00	100.00	100.00

Before the metamorphism of the rock and the consequent formation of spessartite, the iron, manganese, magnesium and calcium now present in that mineral would have been present in the rock in the form of carbonate, analagous to the mixed carbonate, which remains unaltered in the rocks. The Al_2O_3 would have been present in combination with some of the SiO_2 in the form of one of the clayey minerals, and the excess of silica over this amount would be present as free silica. Neglecting the water which would be present in the clay material, an approximate composition can be calculated for the original rock by calculating the amount of CO_2 that would combine with the metallic bases in the spessartite, adding it to the complete analysis and reducing the whole to 100 p.c. :-

	(i)	(ii)	(iii)
SiO_2	21.03	21.15	20.87
Al_2O_3	8.42	9.87	9.68
Fe_2O_3	4.79	7.08	2.53
FeO			3.07
MnO	34.04	33.82	33.90
MgO	0.88	0.83	0.57
CaO	5.11	3.21	4.35
CO_2	25.61	24.04	25.03
H_2O	0.12	-	-
	100.00	100.00	100.00

This gives an approximate original mineralogical composition, regarding the clay mineral as approximating to kaolinite:

	(i)	(ii)	(iii)
Dialogite	70.55	68.98	69.45
Clay Material	15.57	21.49	21.08
Silica	13.88	9.53	9.47
	100.00	100.00	100.00

Thus it is seen that the chocolate-red colour is the result of about $1\frac{1}{2}$ p.c. of disseminated haematite in the rock.

III. The Normal Yellow Material.

Owing to the narrowness of the yellow bands in the ore, it is difficult to select material which is entirely free from associated pink material. The separation was accomplished by chipping and hand selection under the microscope binoculars.

	(i)			(ii)		
	Complete analysis	Insoluble residue	Soluble portion	Complete analysis	Insoluble residue	Soluble portion
SiO_2	21.06	44.23	nil	23.57	45.71	nil
Al_2O_3	3.36	16.62	1.32	9.70	17.01	2.08
Fe_2O_3	4.87	3.63	3.64	0.82	1.04	0.59
FeO		2.44		4.31	3.81	4.82
MnO	41.00	31.82	48.82	40.81	29.54	52.56
MgO	0.73	0.09	1.28	0.68	0.19	1.21
CaO	4.92	1.82	7.56	4.72	1.92	7.64
K_2O Na_2O	negl.	-	-	-	-	-
H_2O	n.d.	-	-	-	-	-
CO_2	19.83	nil	36.73	15.27	nil	31.20
	100.77	100.65	99.35	99.89	99.22	100.10
Insoluble residue	46.03			48.83		

(i) Taken from specimens from near Cell fechan, $1/4$ ml. N. of Barmouth.

(ii) Taken from specimens from the Hendre Mines; N.W. slopes of Moelfre.

The exact composition of the spessartite garnet in these insoluble residues was calculated as before:

(i)

	SiO_2	Al_2O_3	Fe_2O_3	MnO	FeO	CaO	MgO	Total
Spessartite	31.51	17.84		37.23				86.58
Almandite	2.39	1.38			2.85			6.62
Andradite	2.29	-	2.04			2.13		6.46
Pyrope	0.15	0.09					0.10	0.34
Total	36.34	19.31	2.04	37.23	2.85	2.13	0.10	100.00

(ii)

	SiO_2	Al_2O_3	Fe_2O_3	MnO	FeO	MgO	CaO	Total
Spessartite	29.95	16.96		35.41				82.33
Almandite	3.81	2.17			4.56			10.54
Pyrope	0.35	0.20				0.23		0.78
Grossularite	1.84	1.04					1.73	4.61
Andradite	0.61		0.56				0.57	1.74
Total	36.57	20.37	0.56	35.41	4.56	0.23	2.30	100.00

This gives in these analyses (of the insoluble portion) 13 p.c. of SiO_2 with 1.5 p.c. of Fe_2O_3 and 15.2 p.c. SiO_2 with 0.5 p.c. Fe_2O_3 respectively over the amounts necessary to enter into the composition of the garnet. This shows, chemically, a distinct dimunition of the amount of excess Fe_2O_3 in these yellow bands compared with the chocolate-red bands, and microscopically haematite inclusions were observed to be virtually absent from among the garnets in the yellow bands.

It is noted that apart from this difference the mineralogical composition is very much the same as that of the chocolate red material, with the difference that the amount of carbonate is greater in the yellow material. The analyses of the red material show that it forms distinctly less than 50 p.c. of the rock while in the yellow material it forms distinctly more than 50 p.c.

In the same manner as that indicated on (p. 151), the approximate chemical and mineralogical composition of the rock prior to metamorphism can be computed:

	(i)	(ii)
SiO_2	18.69	21.27
Al_2O_3	7.42	8.76
Fe_2O_3	4.32	0.74
FeO		3.89
MnO	36.38	36.84
MgO	0.65	0.61
CaO	4.37	4.26
CO_2	28.17	23.63
	100.00	100.00

Dialogite	73.89	69.97
Clay Material	16.16	16.20
Silica	9.95	13.83
	100.00	100.00

This again tends to show the somewhat greater carbonate content.

IV. The Pale Cream-yellow Material.

The material analysed frequently develops a pale pinkish colour but is more nearly related to the yellow material proper than to the chocolate-red material. Locality: the western side of Mynydd Cwm Mynach.

	Complete analysis	Insoluble material	Soluble portion
SiO_2	19.69	56.55	(1.14)
Al_2O_3	5.10	13.28	0.98
Fe_2O_3	0.97	2.11	0.39
FeO	2.15	0.22	3.13
MnO	43.11	25.82	51.83
CaO	3.73	2.26	4.47
MgO	0.86	negl.	1.29
H_2O	nil	nil	nil
CO_2	24.15	nil	36.51
	99.76	100.24	99.54

Insoluble residue 53.48

The composition of the spessartite as is follows:

	SiO_2	Al_2O_3	Fe_2O_3	MnO	FeO	CaO	Total
Spessartite	32.65	18.48		38.55			89.68
Almandite	0.27	0.15			0.33		0.75
Grossularite	2.14	1.21				2.00	5.35
Andradite	1.55	-	1.30			1.37	4.22
Total	36.61	19.84	1.30	38.55	0.33	3.37	100.00

This gives an excess of 32.05 p.c. silica and 1.24 p.c. of Fe_2O_3 in the analysis of the insoluble residue.

The computed chemical and mineralogical composition of the rock before changes due to metamorphism occurred is as follows:

SiO_2	18.55		
Al_2O_3	4.81		
Fe_2O_3	0.91	Dialogite	76.64
FeO	2.03	Clay Material	10.47
MnO	40.62	Silica	12.89
MgO	0.81		100.00
CaO	3.51		
CO_2	28.76		
	100.00		

The increase in carbonate over the silica-aluminous materials noted in the normal yellow material is carried yet further in the present instance. In addition silica forms a greater proportion, particularly when stated as free silica in the insoluble residue. The amount of clayey materials in the original rock was relatively small and so the amount of spessartite (depending on the Al_2O_3 for its formation) is correspondingly relatively small in the present rock. The amount of free Fe_2O_3 in the insoluble residue is small (and this computed to the analysis of the whole rock is very small indeed), as compared with the chocolate-red material, a deficiency which is reflected in the colour of the rock itself.

V. The bluish-black Material.

These bands as explained in the petrography, owe their colour to the dissemination of small pyrolusite grains, through ore material, which would otherwise be normal in colour.

	(i)			(ii)		
	Complete analysis	Insoluble portion	Soluble portion	Complete analysis	Insoluble portion	Soluble portion
SiO_2	15.48	47.78	-	17.22	56.05	-
Al_2O_3	5.52	15.30	0.86	6.91	14.36	3.65
Fe_2O_3	2.16	1.97	2.24	1.98	1.41	2.23
FeO	2.21	0.37	3.09	2.48	0.39	3.38
MnO	45.76	33.02	51.83	49.10	26.19	59.11
MnO_2	3.49	-	5.15	1.55	-	2.23
MgO	0.75	negl.	1.11	0.74	0.31	0.90
CaO	5.06	1.86	6.58	3.90	1.70	4.86
H_2O-	0.09	-	0.94	0.14	-	-
H_2O+	0.64	-		0.27	-	0.39
CO_2	18.93	-	27.94	16.15	-	23.06
	100.09	100.32	99.74	100.44	100.41	99.81

Insoluble residue: 32.27 50.43

(i) West side of Mynydd Cwm Mynach.

(ii) West side of Mynydd Cwm Mynach.

These analyses are sufficiently identical so that only one need be discussed (ii).

The spessartite in the insoluble residue has the following composition:

	SiO_2	Al_2O_3	MnO	FeO	MgO	CaO	Total
Spessartite	32.88	18.65	38.87				90.38
Almandite	0.48	0.27		0.58			1.33
Pyrope	0.68	0.39			0.46		1.53
Grossularite	2.71	1.53				2.52	6.76
Total	36.75	20.82	38.87	0.58	0.46	2.52	100.00

This gives approximately 1.4 p.c. excess Fe_2O_3 and 31.29 p.c. excess silica in the analyses. It will be noted that this is comparable with the insoluble analyses of the cream-yellow material, which, it will be noted, is from the same locality. The insoluble residue had a distinct pink colour, a fact for which the presence of 1.4 p.c. Fe_2O_3 as haematite would account.

The composition of the rock prior to metamorphism is computed to be as follows:

SiO_2	16.18		
Al_2O_3	6.47		
Fe_2O_3	1.85		
FeO	2.33	Dialogite	74.04
MnO	46.09	Clay Material	14.09
MnO_2	1.46	Silica	8.56
MgO	0.69	Pyrolusite	1.46
CaO	3.66	Haematite (partly in the pyrolusite)	1.85
H_2O	0.38		100.00
CO_2	20.89		
	100.00		

Thus it is seen that the black colour of these rocks is due to the dissemination of only small amounts of fine-grained pyrosulite (in these cases $1\frac{1}{2}$ - $3\frac{1}{2}$ p.c. only in the whole rock) a fact which is comparable with the chocolate-red materials deriving their colour from only $1\frac{1}{2}$ p.c. of disseminated red haematite. It will be noticed that apart from the presence of the pyrolusite, these materials are very similar in nature to the pale cream bands.

VI. The Material Containing the Earthy Aggregates of the Yellow Material.

The material was carefully selected so as to consist as nearly as possible only of the band containing the yellow mineral.

	(i)		(ii)
SiO_2	14.43	Insoluble residue	16.69
Al_2O_3	4.62		6.26
Fe_2O_3	2.21		
MnO	38.68		49.68
MgO	12.94		0.36
CaO	3.49		2.97
K_2O / Na_2O	1.82		n.d.
H_2O+	2.64		very little
H_2O-	0.12		
CO_2	18.67		n.d.
	99.62		75.96

(i) Portion of band with abundant development of the yellow mineral.

(ii) Partial analysis of portion where yellow mineral is practically absent.

The relatively small percentage of MgO in the second analysis coincides with the virtual disappearance of the yellow mineral. The insoluble residue consists chiefly of spessartite.

The calculation of the approximate composition of the Magnesian yellow mineral is based on the assumption that the composition of the rock portion (i) can be accounted for by the presence of the three minerals: dialogite, spessartite and the yellow mineral. The standard for computation is the analysis of the normal ore on p. The ratio of Al_2O_3 to CO_2 associated with the dialogite is 1.3 : 16.87 Therefore in analysis (i) the amount of Al_2O_3 associated with the dialogite is:

$$(1.3 \times 18.98 \div 16.87) \text{ p.c.}$$

$$= 1.46 \text{ p.c.}$$

Therefore the amount of Al_2O_3 in the spessartite is 4.62 - 1.46 = 3.16 p.c. 3.16 p.c. of Al_2O_3 gives by comparison 6.93 p.c. of spessartite, containing 6.20 p.c. of MnO, 0.06 p.c. of MgO and 16.16 p.c. of SiO_2. For the calculation of the dialogite the CO_2 present is taken as the index.

3.49 p.c. CaO = 2.74 CO_2

2.20 p.c. FeO = 1.34 CO_2

1.54 p.c. MgO (in dialogite by computation). = 1.58 CO_2

therefore amount of CO_2 for combination with MnO in dialogite

= 18.67 - 5.66 = 13.01 p.c.

13.01 p.c. CO_2 20.99 p.c. MnO

therefore MnO in yellow mineral = 38.68 - (20.99 + 6.20)

= 11.49

SiO_2 in 16.93 p.c. of spessartite = 6.12

therefore silica available for yellow mineral = 8.27 p.c.

MgO in yellow mineral = 12.94 - 1.44 = 11.50 p.c.

H_2O in yellow mineral = 2.76 p.c.

Composition of Yellow Mineral is therefore approximately equal to:

SiO_2	24.31
MnO	33.78
MgO	33.80
H_2O	8.11
	100.00

Taking the composition of the chlorites, a composition as the above, could be obtained from a mixed molecule consisting of a mixture of Antigorite and Ferroantigorite molecules, i.e. of $3MgO.2SiO_2.2H_2O$ and $3FeO2SiO_2.2H_2O$ respectively. Now antigorite and ferroantigorite contain ideally 43.48 p.c. and 32.25 p.c. of SiO_2. The recorded figure of 24.31 is much too low to satisfy this.

In magnesio-cronstedtite ($2MgO.Fe_2O_3.SiO_2.2H_2O$) the percentage of SiO_2 is 17.85. Thus the presence of the cronstedtite molecule would result in the percentage of SiO_2 becoming much lower. The percentage of MgO in magnesio-cronstedtite is 23.81, thus there is excess MgO in the above analysis, which would also satisfy the excess of SiO_2 necessary for cronstedtite. It is suggested, therefore, that the above analysis indicates a chlorite intermediate between antigorite and magnesio-cronstedtite in which Mn_2O_3 takes the part of Fe_2O_3. Thus the MnO in the above analysis

must be converted to Mn_2O_3:

SiO_2	23.42/60	= 0.3903	(5 × .77)
Mn_2O_3	36.20/158	= 0.2291	(3 × .76)
MgO	32.56/40	= 0.8139	($10^1/2$ × .77)
H_2O	7.82/18	= 0.4343	(6 × .724)

$$\text{Here } s = \frac{SiO_2}{R_2O_3} = 1.704$$

This places the chlorite according to Tschermark in the upper region of the Corundophyllite group, but according to Orcel[1] in the lower region of the Prochlorite group.

This is a chlorite of the type $5SiO_2.3Mn_2O_3.10^1/2.MgO.6H_2O$. If the manganiferous equivalent to Amesite be $Mn_2O_3.2MgO.SiO_2.2H_2O$, antigorite being $3MgO.2SiO_2.2H_2O$, a combination of 3 molecules of the former with one of the latter would give $5SiO_2.3Mn_2O_3.9MgO.8H_2O$, which is quite comparable with the above formula. Thus the composition of the mineral is best represented by a chlorite of the Corundophyllite-Prochlorite transition type.

If these conclusions are correct this brings a new ideal end member for the chlorite group - $Mn_2O_3.2MgO.SiO_2.2H_2O$ corresponding to the amesite type. This is not at all impossible, since the chlorite group is amoungthe most versatile of all mineral groups.

The specific gravity of the yellow mineral can be calculated as follows:

Specific gravity of rock containing yellow mineral = 3.505

Mineralogical composition of the rock:		
	Spessartite	16.93
	Dialogite	47.76
	Chlorite	35.31
		100.00

$$\text{Sp. G. of the chlorite} = \frac{(3.505 \times 100) - (4.15 \times 19.93) - (47.76 \times 3.52)}{35.31}$$

$$= \underline{3.18}$$

This seems to correspond perfectly with what the specific gravity of a chlori of the above composition should be.

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[1] Orcel, M. J. Recherches sur la Composition Chemique des Chlorite. Bull. Soc. Franc. Min. Vol.50. 1927. pp.324-5.

The Petrology of the Ore.

As set forth in the preceding sections, the ore in all its variations consists essentially of an intimate admixture of the minerals dialogite and spessartite with very subordinate quartz, some of the bands only containing relatively small but important quantities of dispersed pyrolusite; the individual grains all have an exceedingly small size.

Chemically the dialogite consists almost entirely of manganese carbonate with only minor proportions of iron, calcium, and magnesium carbonates. It is identical in form and composition with the dialogite occurring in the grits and mudstones, and is also presumably similar to that which occurs in the sphaerodialogite developments associated with the mudstones. Like those occurrences, too, it is essentially colourless and free from inclusions. Consequently the various colours displayed by the ore cannot be due to the contained dialogite; this also, of course, must be true regarding the small quantities of colourless quartz present.

The silicate mineral, which has been proved both microscopically and chemically to be a garnet containing approximately 90 p.c. of the spessartite molecule, appears in the main to be responsible for the colour variations of the chocolate-red and yellow portions of the ore. The isolated crystals, when examined under high powers, clearly exhibit a distinct, though pale, yellow colour; this is the usual colour of the pure spessartites.[1] In the yellow variations of the ore, these crystals are transparent and free from inclusions of any sort and so they are regarded as being directly responsible for the colours displayed. The paler colours of the cream modifications of the ore, typical in the Cwm Mynach localities are explained logically by the fact that they contain a greater proportion

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1 The spessartite in the "gondite" rocks of India (described by Fermor, L.L. "The Manganese ore Deposits of India"; Mem. Geol. Surv. India. vol.XXXVII. p.161. 1909) are orange in colour. In the finer grain of the rocks the colour is often paler: sulphur yellow, pale yellow, cinnamon, or even greyish. Under the microscope the most characteristic is light yellow.

Spessartite containing 31.77 p.c. MnO from the Horse Mts., Llano County, Texas (Penrose, R.A.F. Ann. Rep. Geol. Surv. Arkansas, Vol.I. Manganese; Its Uses, ores and Deposits) is pale yellow in colour.

A reddish amber-yellow garnet containing 37.98 p.c. of MnO is recorded by Shannon, S.V. (Blythite and the Manganese garnet from Amelia, Virginia; Journ. Wash. Acad. Sci. 1927. Vol.17. pp.444-52.)

of the colourless component (dialogite) as compared with the normal yellow developments.

The minute garnets, isolated from the reddish bands of the ore, are almost invariably found to contain very minute inclusions, which on chemical grounds are regarded as being haematite. These inclusions vary from a few well defined ones usually confined to the centre of the crystal to more cloudlike masses, either dispersed throughout, or confined to the central portion of the crystal. These reddish inclusions, although never exceeding 2½ p.c. of the crystals, are sufficient to impart to it a reddish tinge. It is, therefore, concluded that vmiations in the colour of the red type of the ore is due to the presence of varying but small quantities of finely disseminated haematite contained within the minute crystals of spessartite, which form 50-60 p.c. of the ore. The normal "gondite" rocks of the Dhárwár facies of India vary in colour from cream (rare), through grey, yellow, buff, cinnamon, to reddish and purplish. "The microscope shows that those varieties that show purplish or reddish tints in hand-specimen do not as a rule owe their colour to the garnet being purple or red; but to the fact that the separate grains of garnet each contain a small cloud of finely divided red dust, probably oxide of iron, sometimes uniformly distributed throughout the grain, but more often collected in the central parts of the grain, so as to leave the periphery clear".[1]

The garnet has a very uniform composition throughout the ore, and is a remarkably pure spessartite: the MnO content varies from 35.41 p.c. to 38.87 p.c. averaging 37.83 p.c., and the percentage of spessartite molecule from 82.35 p.c. to 90.38 p.c., averaging 87.98 p.c. Iron and calcium molecules (almandine and probably both grossularite and andradite) and to a lesser extent pyrope, also enter into the composition of the garnet. For the sake of comparison analyses of spessartites from other localities are given:

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[1] Fermor, L.L., op. cit. p.338.

	I	II	III	IV	V
SiO_2	36.34	36.51	35.93	35.66	35.76
Al_2O_3	19.31	20.22	18.08	18.55	21.06
Fe_2O_3	2,04	0.68	4.60	0.32	1.78
FeO	2.85	1.79	-	14.25	-
MnO	37.23	38.72	31.77	29.48	39.40
CaO	2.13	2.08	8.48	1.15	1.23
MgO	0.10	-	0.69	0.88	1.46
	100.00	100.00	99.55	100.33	99.69

	VI	VII	VIII	IX	X
SiO_2	35.35	36.65	36.16	37.06	37.73
Al_2O_3	20.41	20.93	19.76	21.96	21.26
Fe_2O_3	2.75	-	-	-	-
FeO	1.75	5.67	11.10	20.05	9.94
MnO	38.70	37.21	32.18	20.41	24.48
CaO	0.94	0.48	0.58	0.08	3.11
MgO	0.27	-	0.22	tr.	3.48
	100.17	99.94	100.00	99.56	100.00

I Merionethshire; yellow ore (see p.150)

II " chocolate-red ore (see p.153)

III Horse Mountain, Hano County, Texas; Penrose, R.A.F., Ann. Rep. Geol. Surv. Arkansas. Vol.I. Manganese: Its Uses, Ores and Deposits. p

IV Nathrop Colo.; Eakins, Amer. Jorn. Sci. XXXI. p.435. 1886.[1]

V Tsilaisina, Madagascar; Duparc, Wunder and Babot: Les Minéraux des Pegmatites des Environs D'Antsirabé a Madagascar, p.404. 1910.[1]

VI Amelia County, Va.; Clarke, U.S.G.S.; Bull.60. p.129. 1890.[1]

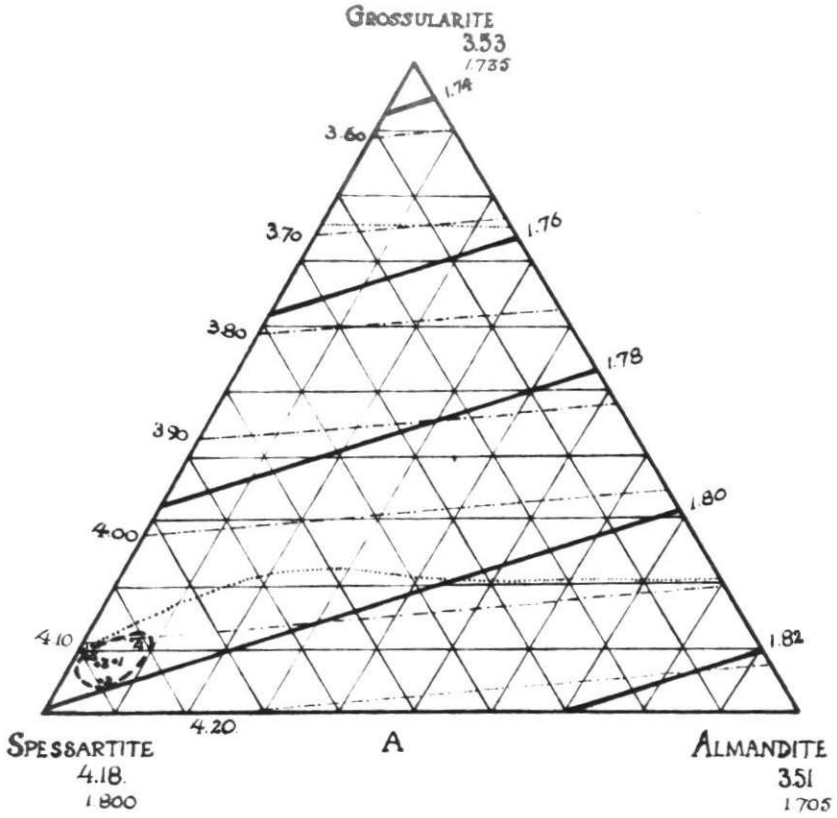
VII Branchville, Conn.; Penfield, Dana's System Min., 6th Ed. p.442. 1886.[1]

VIII Haddam, Conn.; Rammelsberg; Journ. pr. Chem., lv. p.487. 1852.[1]

IX Pala, San Diego, Cal.; Schaller, Published by permission of the Director of the U.S. Geol. Surv.[1]

X Wagora Chhindwára district, India; Fermer, L.L. The Manganese-ore Deposits of India; Mem. Geol. Surv. India. Vol.XXXVII. 1909. p.351.

[1] Cited by Ford, W.E.: "A Study of the Relations existing between the Chemical Optical and other Physical Properties of the Members of the Garnet Group". Amer. Jour. Sci. xl. pp.34-5. 1915.


GROSSULARITE
3.53
1.735
1.74
3.60
3.70
1.76
3.80
1.78
3.90
1.80
4.00
4.10
1.82
4.20
SPESSARTITE
4.18.
1.800
A
ALMANDITE
3.51
1.705

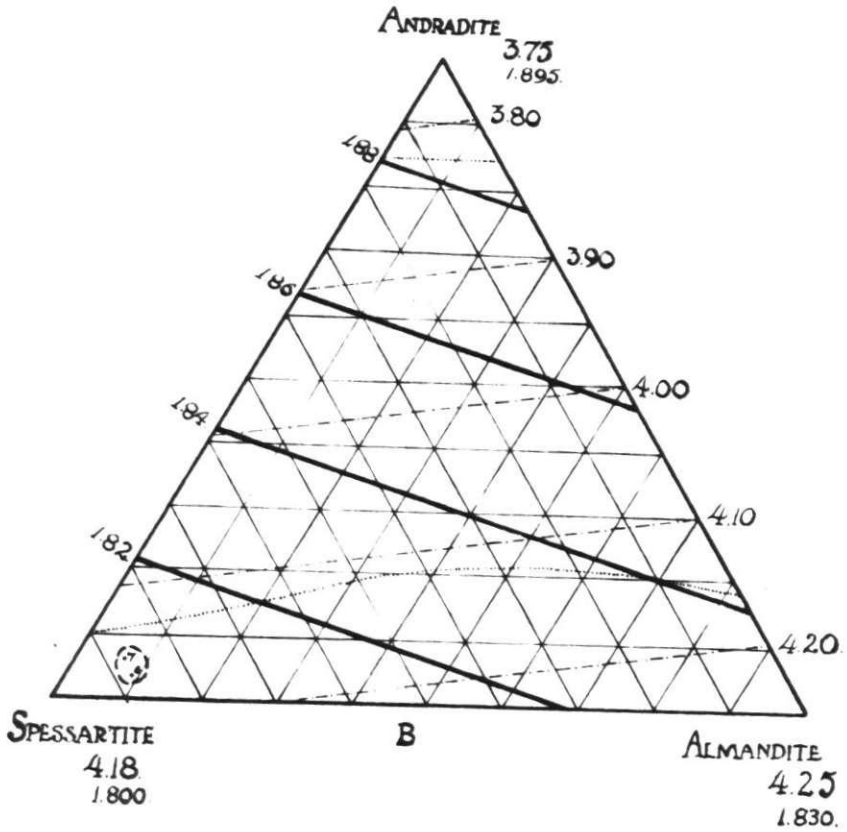

ANDRADITE
3.75
1.895.
3.80
1.88
3.90
1.86
4.00
1.84
4.10
1.82
4.20
SPESSARTITE
4.18.
1.800
B
ALMANDITE
4.25
1.830.

Fig. 30.

The compositions of the garnets in the manganese ore (pp. 146 - 158) are plotted upon Ford's graphs showing the relationships between the chemical composition and the specific gravity and refractive index of members of the garnet group (Amer J. Sci. CXC. 1915 p. 33.) The dotted lines repesent the limits of crystal solubility, the broken lines the specific gravity of the unbroken lines the refractive index.

Graph A. shows those in which the spessartite, almandite and grossularite molecules are predominant, and B those in which andradite is calculated to take the place of glossarite. The pyrope which is always present is neglected because its proportion is always insignificant.

I.	((i), p. 150)	S.G.	4.13	R.I.	1.796
2.	((ii), p.150)		4.15		1.798
3.	((iii), p. 151)		4.13		1.796
4.	((i), p. 154)		4.10		1.794
5.	(p. 157)		4.13		1.795
6.	(p. 148)		4.15		1.806
7.	(p. 153)		4.17		1.807

By plotting the compositions of the garnets as set forth on pp.146-57 in the preceding section, on the graphs prepared by Ford[1] theoretical values for the specific gravity and the refractive index can be read (see fig. 30). The theoretical values for the specific gravity vary between 4.10 and 4.17 ; the value obtained by computation from the composition and specific gravity of the rock is 4.135 ; this shows a high degree of accordance. From these graphs the refractive index of the garnets varies between 1.794 and 1.807

Although garnet does occur rarely as a primary mineral in igneous rocks, by far its most common occurrence is as a secondary product due to metamorphism (usually regional), and it is, up till now, unrecorded as a primary mineral in sediments.[1] The production of spessartite in the manganese ore is therefore regarded as being the result of metamorphism, the grade of which must be the same as that of the interbedded mudstones, which is fully described on pp.83-98. Since the metamorphic grade of the mudstones is low, that of the manganese ore itself must be low, even though over 50 p.c. of the rock was completely converted to garnet, which is usually regarded as representing a fairly high grade of metamorphism. Fermor notes that frequently, e.g. in the Bálághát region, only relatively low grade metamorphic argillaceous rocks are associated with the spessartite-quartz rocks of the "gondite": "Frequently", he states, "they have not passed the slate stage".[2] The full significance of this relatively early appearance of spessartite on a large scale has been discussed earlier in this thesis. The abundant development of spessartite in the ore is directly correlated with the existence in the more of abundant available manganese, as carbonate, in the presence of aluminous clayey materials. The exceedingly small size of the individual crystals suggests the ease with which crystallisation was initiated, the centres of growth being so numerous that all the available materials were used up before any of the crystals could reach any marked size. In addition, the uniform size of the crystals

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1 P.G.H. Boswell (On the Mineralogy of Sedimentary Rocks, 1933, p.102) throws doubt on the only one recorded occurrence of anthigenous garnet: that described by A. Saner from the neighbourhood of Heidelberg (Granat als authigener Gemengtheil im bunten Kenper. Ber. oberrhein. geol. Ver., XXXIII. pp.42-6. 1900.

2 op cit. p.311.

indicates that all the centres were initiated contemporaneously. Fermor found that spessartite was formed before rhodonite in the metamorphism of the Indian ores, and if was only after all the available alumina had been exhausted that rhodonite formed.[1] In the present case spessartite was formed by the combination of manganese carbonate with clayey-siliceous materials under conditions of relatively high pressure:

$3MnCO_3 + Al_2O_3.2SiO_2 + SiO_2 = 3MnO.Al_2O_3.3SiO_2 + 3SiO_2$
(dialogite) (clay) (silica) (spessartite)

The large amount of dialogite still existent in the ore represents the excess of dialogite over the clayey materials in the original rock with regard to the proportiona necessary to form spessartite. Although no significant quantities of clayey materiaks now exist in the rock, the cohsiderable amounts of spessartite present testify to their original existence in fair proportions. Before metamorphism, therefore, the ore consisted of an admixture of dialogite, clayey materials, and silica, and this must have been its constitution at the time it was formed.

The sedimentary nature of the ore.

The very obvious concordance of the ore band with the beds below and above it points to the conclusion that it is undoubtedly of contemporaheous origin: it is everywhere at exactly the same horizon; it is always underlain by a green mudstone containing pyrite; the Bluestone above it always has the same character and varies little in thickness, and thus can always be shown to be overlaid by a more gritty horizon - the Bluestone Grit; the ore band itself maintains a relatively constant thickness; the characteristic banding of the ore is always perfectly parallel to the major bedding planes of the associated normal sedimentary rocks; and finally, the ore band often merges above and below with these normal sedimentary mudstones. Its uniform, exceedingly fine grain and its uniformly high original manganese carbonate content (upwards of 70 p.c. +), rule out the possibilities of its being a volcanic deposit. It has been suggested that it may be a limestone which has been metasomatically altered.[2] If this were so, one would expect the residual CaO content to be somewhat variable, whereas actually it is remarkably constant and low, Also, if there had been metasomatic changes on such a

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[1] op. cit. p.290.

[2] Fearnsides, W.G.: North ahd Central Wales, Geology in the Field (1910) p.792.

large scale, it would seem probable that the grain size of the altered rock would vary somewhat from place to place, whereas actually it is remarkably uniform.

It must therefore be a normal sedimentary member of the vast thickness of the Harlech Grit Series, the mudstones and grits of which were laid down in the normal manner subaqueously. These grits and mudstones must have been deposited in shallow waters close to the shore line. This is especially true of the grits, which are often very coarse and contain felspars which are very fresh. Since the ore band forms a component part of this series, it, too, must have been formed in shallow water; catastrophic changes would be necessary to explain any marked changes of depth from the obviously shallow water of the Bluestone Grit only a few feet above the ore. In this connexion it is well to point out the fallacy of the idea that sedimentary manganese deposits all originate at great depth. This appears to have arisen out of the fact that manganese dioxide nodules are dredged from abyssal depths in the oceans. Penrose cites evidence for believing that the manganese of Arkansas was deposited in shallow water: "The St. Clair limestone contains numerous fossils ..... characteristic of a shallow water deposition. The occasional beds of sandstone in the limestone also lead to the belief that the deposition took place near the shore; while the occurrence, in an undecayed state, of such an easily decomposed mineral as feldspar suggests that the distance from its source to its present resting place was short".[1] Manganese oxide is formed associated with the Fransiscan cherts, which are believed by Davis to be of shallow water origin.[2] It has been suggested that manganese oxide is precipitated at abyssal depths, whereas manganese carbonate may be more characteristic of shallower water. It is interesting to note that E.M. Kindle reports manganese dioxide concretions from the shallow waters at the edges of some of the Canadian lakes.[3]

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1 Penrose, R.A.F. Ann. Rep. Geol. Surv. Arkansas. Vol.1. p.589.

2 Davis, E.F. "The Radiolacian Cherts of the Fransiscan Group"; Univ. Calif. Pub. Bull. Dept. Geol. Vol.11. No.3. pp.235-432. 1918.

3 Kindle, E.M. "Manganese Concretions in Nova Scotia Lakes". Trans. Roy. Soc. Canada. 3rd Ser. Section IV. Vol.XXXX. (163-80) (1935).

The ore chemically deposited. The ore rock, being regarded as a subagueous sedimentary rock, may have accumulated by detrital, organic or chemical means. The complete absence of any grains of a detrital nature, coupled with the relative absence of minerals characteristic of detrital sediments (only small amounts of quartz are present and these do hot bear the marks of a detrital origin) make it improbable that the bed was the result of detrital sedimentation. In the complete absence of any sort of organic remains whatsoever, it seems hardly necessary to seek an origin in that direction.

Many of the structures exhibited by the ore point to the conclusion that it was deposited colloidally as a gel, by chemical means. The most significant of the facts which suggest this colloidal origin can be enumerated as follows:-

(a) The uniform, extremely fine-grained nature of the rock. Even in its present state, after much crystallization, with formation of new minerals, the average grain size is only 0.015 mm. If anything its original grain size must have been of an even finer nature than this. This would give an original truly cryptocrystalline grain size, characteristic of the crystallization of a colloidal gel.

(b) The peculiar irregular banding, particularly characteristic of the normal yellow layers (Fig.25): the irregular thickening and thinning of the bands; the abrupt endings of the layers, the terminations being quite rounded; the splitting up of a layer into a series of separated portions, all the margins of which are quite rounded, and the transition of these separated portions into bodies of a true lenticular nature. Of these the blunt rounded terminations are most significant from the point of view of the gel-origin. E.F.Davis obtained similar irregularities of banding in colloidal materials in the following manner: "A suspension of clay was mixed with a moderately strong solution of sodium silicate. Above the mixture thus produced a solution of ammonium carbonate was poured..... As the ammonium carbonate diffused down it produced a flocculation of the silicic acid, and in the formation of the gelatinous silica a banding resulted, consisting of alternate layers of fine clay, and clear silica jelly.....

"The bands varied somewhat in width in different experiments. They were approximately equally spaced and while fairly regular, they showed.....

lenslike terminations of both clay and silica bands; they showed an irregular thickening and thinning. Some nodules were formed."[1]

The structures, artificially produced in a gel-flocculation, are therefore very similar to those existing in the ore.

(c) The spheroidal bodies of yellow material. These are very characteristic of the ore (see figs. 28 and pp. 135-7). Much work has been done on the formation of natural oölitic, spherulitic and spheroidal structures, and it is now generally regarded that nearly all such structures arose from what was originally material of a colloidal nature. H. Schade[2] has demonstrated that concretionary bodies result when a substance passes from the state of an emulsion colloid to that of a solid, and that if the change leads to a crystalline state the resulting structure is radial if the substance is pure, and concentric if other substances are precipitated along with it. The spherical shape is due to the tendency of the droplets, formed during the separation of the dispersed phase, to coalesce. The spheroidal bodies possess a well-marked concentric structure with two or three distinct zones. The present mineralogical composition (spessartite and dialogite) show that the materials forming the spheroid originally were two phase - manganese carbonate and clay, and in accordance with Schade's theory the structure became concentric by crystallization of this heterogeneous mixture. Since the central and external zones of the spheroid can often be shown to contain more spessartite than the intervening zone (they are frequently partially isotropic, while the separating zone is uniformly anisotropic) it follows that the concentric structure is a result of diffusion of the aluminous materials towards the central and external portions of the spheroid. The work of Liesegang[3] has made such concentric diffusion in gels familiar.

It is interesting to note that S.C. Bradford[4] records that when 1 p.c. agar gel in which small quantities of either liver of sulphur or

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1 Davis, E.F.; op. cit., pp.399-402.
2 cited by Bucher, W.H. in Journ. Geol. Vol.XXII.
3 Liesegang, R.E.: "Geologische Diffusionen". Dresden, 1913.
4 In a letter to Nature, Vol.97. p.80. (1916).

manganese sulphate had been dissolved, was treated with the other reagent, many of the zones of the resulting stratification were separated into a number of concretions, which in some cases were joined by rods to those of the succeeding zone. The concretions were all sharply defined.

G.I. Taylor[1] with the aid of a special apparatus pulled out a drop of viscous oil suspended in a syrup into a thin thread. When the apparatus was at rest and the pulling forces on the thread had ceased, the thread gradually broke up into a number of small spherical drops. The chief conditions necessary for the splitting up of the thread into such drops appears to be that the thread material should be more viscous than the material enclosing it and that a definite surface tension should exist between the two components. It therefore seems possible that if a thin layer of gel-like yellow material were enclosed between thicker layers of a gel-like red material, if the former were slightly more viscous than the latter, and if a definite surface tension existed between them, then the yellow layer might split up into a series of spherical bodies, which during consolidation would become compressed into spheroidal forms due to the weight of superimposed material. Regarding the relative viscosities of the two materials originally nothing can be said, but the fact that the junctions between the normal yellow layers and the normal red materials are always very sharply demarcated even under the higher powers of the microscope, seems to indicate that a very definite surface tension existed between the two components, which prevented their intermingling at the surfaces of contact. It is the existence of a definite surface tension between them that would actually cause the formation of the globules, and it would be this surface tension that would cause the ends of separated portions of a yellow layer to assume a blunt and rounded form. If some such method as this caused the formation of the spheroidal bodies they were obviously formed immediately after the deposit itself collected, before any hardening and consolidation commenced.

(d) The laminae of the chocolate-red material. The essential characters of these are: their remarkable regularity; their unbroken natur when traced laterally (cf. the banding of the yellow material); their paral elism with the margin of the red layer in which they are developed; their

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1 "The Formation of Emulsions in Definable fields of Flow", Proc. Roy. Soc. Ser.A. No.858. Vol.146. p.510. (1934).

uniformly small thickness; the regular variation of their distance apart this shows a slight increase towards the central portion of the band; their composite nature, the "red" laminae containing a relativeky large amount of red material scattered in a colourless to pale yellow base, and the "colourless" layers merely very small amounts of red material in the same base. The red banding is the result of the laminar segregation of the haematite inclusions of the spessartite garnets of the red layers.

This structure bears a remarkable similarity to the Liesegang Ring phenomenon caused by precipitation within gels, and is similar to the banding of agates. "It is often observed", states Freundlich[1], "that a solid phase of a difficult soluble substance does not separate uniformly in a gel, but forms regaular layers." The layers succeed one another in the direction of the diffusing precipitant, and their planes are at right angles to this direction. In the present instance, the direction of diffusion would be at right angles to the bedding and so the laminae themsleves are parallel to the bedding. "Microscope observations of the stratifications have been made by Liesegang himself and by later investigators. Only in a few reactions ..... are the "clear" spaces between the rings practically free from the insoluble compound: in most cases the rings contain a large number of small, and the clear spaces a small number of large, crystals or crystalline aggregates"[2]. This is in accordance with the statement that th "red" laminae contain relatively large amounts of red material, while it is not entirely absent in the "colourless" laminae.

Sargent[3] states that a coarse horizontal banding in light and dark layers, "possibly due to segregation of impurities by crystallization" is not uncommon, in the charts of the Yoredale Series. Davis[4] states: "One very characteristic feature of the cherts of the Monterey Group is the minute lamination. Each bed of chart shows a great number of fine bands of different colour, or different shades of the same colour, parallel to the bedding of the chart. These bands are so thin that there may be twenty to

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1 Freundlich, H.: Colloid and Capillary Chemistry, London, p.732.1926
2 Hatschek, E.: "The Liesegang Phenomenon". 2nd Rep. on Coll. Chem., B.A. Rep., p.23. 1919.
3 Sargent, H.C.: "Further Studies in Chert". Geol. Mag. Vol.66. p.405. 1929.
4 Davis, E.F.: op. cit. p.284.

thirty of them in a layer of chert an inch in thickness ..... The cherts show very little tendency to cleave along the laminae." Both these authors regard the cherts concerned as having been originally colloidal silica gels, but neither directly correlates the lamination with the Liesegang phenomenon.

It is suggested that the lamination resulted from the periodic precipitation of iron hydroxide within these layers of the ore material contemporaneously with or immediately after its formation as a gel. This iron oxide was taken up by the spessartite as inclusions in situ, so that the present distribution of the haematite inclusions of the spessartite represents the original distribution of the haematite as layers within the ore gel.

(e) The patchy nature of the cream-coloured ore layers. The patchy colour variations observed in this section, and which reflect slight differences in constitution are regarded as indicating a colloform nature.

(f) Contraction Cracks (Syrenesis): These are fully described in the preceding section (pp.136-9), and the evidence cited for regarding them as contraction phenomenon quite distinct from ordinary veining. Most authorities regard the existence of contraction cracks and cavities as the most common and conclusive evidence of derivation from a colloidal gel.[1] Numerous veins, chiefly quartz-filled, varying in size from those which can scarcely be seen with a microscope to some a quarter of an inch thick occur in the cherts of the Fransiscan Group.[2] These are confined to the cherts and do not extend into the shales, and are orientated normal to the bedding.

These contraction cracks are considered to have resulted from the contraction of a gel consequent upon its dehydration. The material infilling the veins is very fine-grained manganese carbonate, and this indicates that they were formed not long after the deposition of the band, since the same material was available to infill the cracks as actually formed the major portion of the deposit itself. The relationships of the contraction cracks to the other structures of the ore - the spheroidal bodies, and the patchiness of the cream-material - clearly point to the conclusion that these latter structures

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[1] see, e.g. Cox, Dean, and Gottschalk; "Studies in the Origin of Missouri Cherts and Zinc Ores". Chem. News. 115. p.53. (1917).

[2] Davis, E.F.; op. cit. pp.259-60.

predate the contraction cracks; consequently they must have originated while the deposit was in the true gel state and are not subsequent structures due, say, to crystallization.

Thus all the main structures desplayed by the ore can be explained by the assumption that the ore was originally in the state of a colloidal gel. Although some of the structures could be individually explained by other means it is only the colloidal hypothesis that explains them all simultaneously, and, therefore, the conclusion is reached that the ore material was precipitated colloidally and was before consolidation a typical gel.

Regarding the actual original constituents of the ore, they have already been stated to have consisted of manganese carbonate, clayey and siliceous materials. The existence of the two latter forms as gels in nature is well-known and clays when deposited nearly always have a colloidal nature. There is, in addition some direct evidence for believing that the manganese carbonate itself had a colloidal form[1]. The residual manganese carbonate within the ore, has the form of minute, somewhat irregular, globular bodies, devoid of any radial, concentric, or, in fact, of any crystalline characters at all beyond anisotropy. It would hardly seem possible that a mixture of about 30 p.c. gel material and 70 p.c. non-colloidak material would possess a sufficient gel-like character to enable such structures as are above enumerated to originate. If these structures, perfect as many of them are, indicate a gel-origin at all, it would seem that in all probability the material forming them would be of a homogeneous gel-character and not merely a mixture of gel and non-gel materials, especially with such a large proportion of the latter.

The ore, therefore, is believed to have been deposited by chemical means: precipitation of manganese carbonate in a colloidal form from solution proceeding simultaneously with the flocculation of clayey and siliceous gel materials in the absence of ordinary detrital sedimentation with occasional precipitation of manganese hydroxide (in the blackish bands)

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[1] Some evidence for this has already been stated (see pp. 128-9)

and of iron hydroxide (in the chocolate-red bands). It has been shown (pp. 35-7) that such action was going on, during the deposition of the grits and mudstones, contemporaneously with normal sedimentation, and it was absence of the latter that allowed the formation of a deposit very rich in manganese carbonate.

The different bands of the ore rock vary slightly in chemical and mineral composition; such variations resulted from changes in conditions which in the case of the regular alternation of red and yellow materials may indicate a seasonal variation of some sort, but the exact mechanism of these changes is not known.

II. General Considerations.

The sources of the materials. The aluminous and siliceous materials resulted from the normal disintegration of a largely gneissic land mass. It has been shown that these materials were constantly being transported into the area of deposition in colloidal suspension. When detrital sedimentation ceased, i.e. when there was a suspension of active degradation, the only materials to be brought in suspension into the basin would be these exceedingly fine grained suspensoids which are taken up more or less in chemical solution. On reaching the quick waters of the basin of deposition, these would be flocculated by the action of dissolved salts and gravity.

The manganese was derived from the preexisting rocks. The earth's crust contains on an average about 0.10 p.c. of manganese oxide, most of which is distributed (apart from actual manganese ores) in insignificant quantities in the various ferromaghesian minerals. Minerals containing relatively high proportions of manganese have an important rôle in the formation of some igneous rocks. There is considerable evidence for believing that most of the original manganese of the earth's surface is contained in the Pre-Cambrian rocks. The largest manganese deposits of the United States and of Canada are in the neighbourhood of such rocks. It is found that large areas of bog manganese occupy basins on the surface of the Pre-Cambrian Shield.[1]

Three facts point to the derivation of most of the world's available manganese from the Pre-Cambrian rocks: (i) The occurrence of large bodies of rich deposits in the Pre-Cambrian rocks themselves, e.g. in the Kuderite Series of Vizagapatam and Ganjam; in the Gondite Series of Narukot State, Jhabna State, and certain districts of the Central Provinces (both Archaean occurrences in India); in the State of Minas Geraes in Brazil, where they occur in rocks of the Archaean Group in the Basement Complex. (ii) The occurrence of large quantities of ore in the Lower Palaeozoic rocks, and which could only have been derived from the preexisting Pre-Cambrian rocks. (iii) Where manganese deposits occur, which cannot be placed in either of these categories, it is usually seen that they are situated on, or

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[1] Penrose, R.A.F.; Manganese; Its Uses, Ores and Deposits; Ann. Rep. Geol. Surv. Arkansas. Vol.1. p.542.

at the edge of old Pre-Cambrian masses, e.g. manganese ores occur in Miocene Strata in the Caucasus, resting on the edge of the Baltic Shield; in the district around Nikopol on the Dneiper in the Government of Ekaterinoslav, where the deposits occur in Oligocene strata resting on granite and gneiss of Archaean age; in the Urals, again resting on the edge of the Baltic Shield.

The manganese went into solution probably as sulphate or bicarbonate and was precipitated as carbonate on reaching the basin.

Relationships of Manganese and Iron in the Deposits: The ratio of manganese to iron in the earth's crust is approximately 1:60[1], and yet in the Merionethshire Cambrian ore bed the proportion of manganese is very much greater than that of iron. It is very difficult to explain what has become of the much larger amounts of iron that must have been removed from the land mass simultaneously with the manganese during degradation. Penrose[2] suggest in dealing with a similar problem in connection with the Arkansas manganese deposits, that the iron and manganese were separated by mechanical means, and that the iron being deposited in a different area from the manganese has since been eroded. In the complete absence of what must have been relatively extensive iron deposits, this argument does not appear to be conclusive when applied to more than one area.

Manganese is taken into solution by natural waters more readily than is iron, and incoluble iron salts tend to be precipitated before the corresponding manganese salts, i.e. manganese salts tend to be relatively more soluble than the corresponding iron salts. Thus when manganese and iron are present in the rocks undergoing erosion, the ratio of mangahese to iron in the resulting solutions is somewhat greater than the ratio in the original rocks. More of the iron would be carried away as insoluble material than would be the case with the manganese, and the proportion of iron in solution would tend to be kept relatively low by constant precipitation while the small amounts of manganese in solution would gradually accumulate. Immediately before the formation of the actual ore band began, the waters contained considerable quantities of manganese in

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[1] Beyschlag, Vogt and Krusch; Ore Deposits, London, p.851. (1914).

[2] Ann. Rep. Geol. Surv. Ark. Vol.I. Manganese, its Uses, Ores and Deposits. p.593.

solution together with a greater amount of iron than is actually represented by the composition of the ore band itself. Precipitation took place under reducing conditions, the precipitating agents being hydrosulphurous acid (probably in the form of soluble alkaline sulphides (see pp.), and carbonic acid (probably in the form of soluble alkaline carbonates). Other things being equal the sulphides are the more powerful precipitant, and tend to act first. But manganese sulphide is very unstable and so would not be formed; thus iron sulphide is first precipitated, while the main bulk of manganese still remains in solution. This explains the formation of the continuous layer of iron pyrites, which everywhere underlies the ore. The major portion of the iron was thus removed from solution and further precipitation resulted in the accumulation of a deposit relatively enriched in manganese.

The manganese with the rest of the iron was then precipitated as carbonate, the actual precipitation in this form depending on the reducing environment afforded by the presence of sulphide in solution: "When manganiferous solutions in the form of surface waters are protected from oxidation by being in the presence of a reducing agent, such as vegetable or animal matter, they are often precipitated as carbonate. The bicarbonate or other salts of manganese that are in solution, however, are so easily oxidized that unless the protection from oxidation is very complete, the manganese is precipitated as oxide ...."[1] Manganese sulphide would not be formed under the action of this reducing agent, since it is a very unstable salt, which only occurs in nature in very rare instances, and then only in metallic bodes and veins. Occasionally during the deposition of the ore, the reducing medium became relatively less strong, permitting the co-precipitation of small quantities of manganese dioxide in what are now the dark blue-black layers of the ore.

Throughout the period of precipitation of the ore band there was simultaneous flocculation of colloidal clayey materials (see above) and in this connection it is interesting to note the effect that these two components may have had in precipitating and flocculating each other. It is a well known fact that relatively large proportions of dissolved salts have a distin

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[1] Penrose, R.A.F. Geol. Surv. Ark. loc. cit. p.553.

effect in producing the flocculation of colloidal material, and that this effect varies directly with the concentration of the dissolved salts.[1] On the other hand the strong adsorption powers of colloidal materials result in these materials removing, by their own power, considerable amounts of dissolved materials from solution. "If an aqueous ten per cent solution of $CnSO_4$ be filtered through 20-30 grms. of refined kaolin the filtrate will be practically non-metalliferous.... The settlement of slimy material is not only promoted by salts, but such material itself may be adsorption precipitate metallic salts and oxides."[2]

The formation of the strata below the ore was not characterized by any marked precipitation of manganese, but the mudstones above the band, and in particular the Bluestone shew a considerable proportion of the manganese carbonate. The actial accumulation of manganese in such quantities as to form an ore merely depended on the temporary suspension, at that time, of normal detrital sedimentation. The fact that the precipitation of large quantities of manganese carbonate began more or less at a period when such sedimentation was at a standstill may or may not have been a coincidence.

A period when ordinary detrital accumulation ceases usually marks a period of drought, a period when the rivers entering the basin of deposition are small in volume, and during which evaporation would be excessive. Such evaporation might explain why active precipitation more or less began at this period. It most certainly seems to account for the continued precipitation of manganese throughout the thickness of the ore. Little manganese could have been added to the waters in the absence of detrital sedimentation, the evidence for active degradation on land. In a natural water expanse a supersaturated solution of manganese is hardly likely, and so continued evaporation is necessary to explain the maintenance of the manganese at precipitation point, if none is added to solution.

The Palaeogeography of Harlech Grit Times.

Several facts favour the belief that the deposits containing the

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1 Freundlich, H. op. cit. pp.
2 Beyschlag, Vogt and Krusch; Ore Deposits (1914) pp.974.

manganese ore band, viz. the Harlech Grit Series, were laid down in an enclosed basin of deposition. These can be enumerated briefly as follows:

(i) It is believed, for reasons set forth above, that the ore originally formed a relatively thick gel-like deposit, throughout which occurred many delicate structures. All these structures are well preserved and show no signs of having been distorted after they were formed, that is, after the deposition of the band. In an ordinary detrital deposit, the fragmental nature of the deposit would permit of resorting under the action of moving waters, so that the final deposit would not show any signs of such action; such resorting would, however, be impossible in a gel-like deposit. Any response to water movements would be at least to slightly deform the structure of the deposits. In the absance of such deformations it is believed that the waters, in which the ore was formed, were very quiet, and that waves and currents were practically non-existent. Such would be the conditions within an enclosed or partially enclosed basin.

(ii) Communication with large tracts of open water must have been difficult, since the concentration of large amounts of manganese salts in solution indicates that there was no freedom of diffusion. Such abnormal concentrations of unusual salts is barely possible in ocean water. In an enclosed basin the concentration of salts would gradually increase as more and more were brought in by the rivers, whereas in open water they would diffuse and never reach a sufficient concentration to permit of the precipitation of a large deposit.

(iii) It is quite clear that land lay no far to the east: the grits thicken and become more numerous eastward, and the freshness of the felspars and the angularity of the quartz grains in the grits, show that they are not far-derived. To the west, the extension of the Harlech Grit Series is seen in the Cambrian rocks of the St. Tudwals peninsula.[1] Nicholas states that there is no evidence whatever of any approach to a shore-line in this westerly direction and that "the westward thinning so well marked in the Harlech Dome is carried slightly farther in the Lower and Middle Cambrian of the St. Tudwal's Peninsula and that, like the Cambrian and Merionethshire,

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1 Nicholas, T.C. The Geology of the St. Tudwal's Peninsula (Caernarvonshire) Q.J.G.S. Vol.LXXI. pp.83-141. (1915).

its main supply of sediment came from the east."[1] The fact that the Hell's Mouth and Cilan Grits both contain more fine-grained material relatively than their counterparts the Rhinog and Harlech Grits is cited as evidence supporting this, but scarcely for the same reason, the fact that the Mulfran Beds are more gritty than the Manganese Shale in the western part of the Dome must point to a source in the opposite direction. "Above (the maganese horizon) follow about 400 feet of somewhat similar beds; but grits are much more abundant, and appear to make up half the total thickness".[2] Actually Nicholas correlates the lower part of the Cilas Grits with the upper part of the Manganese Shale Group. So some evidence does exist for believing that land lay to the West. The petering out of the manganese ore eastward on Y Garn indicates the approach to a shore-line in that direction. In the St. Tudwal's Peninsula, though the horizon is clearly marked, the ore in its characteristic form is absent and so this may indicate the approach to land in that direction. It seems reasonable to believe that the true ore was confined to the central portion of the basin of deposition.

To the south of the presence of a land barrier is indicated by the southward coarsening of the Bluestone Grit when traced from the Diphwys region to Barmouth. This coarsening is even more marked than that from Diphwys towards Cwm Mynach. In addition the great difficulty in comparing the lower Cambrian rocks of Pembroke with those of the Harlech region points to their separation.

To the north, the evidence is more obscure. There is a remarkable increase in thickness of the grits of the Forty Feet Grit in the Moel Ysgyfarnogod region. The variations inthickness between the Harlech beds and their suggested equivalents in the Nantlle region is not easy to follow, while the apparent absence of any manganese horizon in that locality is hardly compatible with the idea of a continuous sheet of water. A narrow ridge of land or possibly a shoal may have separated the Harlech area from that of Nantlle during the time of deposition of the Manganese Shales.

(iv) The associated sediments themselves, especially the grits have characteristics of continental basins of deposition; the presence of

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[1] op. cit. pp.138.
[2] loc. cit. pp.91.

fresh felspars in particular is noteworthy. "In their main lithic characters" state Cox and Wells, "they are not markedly different from deposits which in other areas, have been unhesitatingly classed as continental".[1]

(v) In this connection, also, it is interesting to note the occurrence of sphaerodialogite among the mudstones (see pp.117-130). Regarding such deposits, Spencer[2] states that they "seem, without exception, to be of freshwater origin ....."

(vi) The evidence of manganese deposits elsewhere: The manganese ore of the Lower Cambrian of the Appalachian region was supposed by J.D.Dana[3] to have been laid down in marshes and coastal lagoons, where all conditions necessary for the deposition of the oxides and carbonates of manganese, and, in some cases the sulphide of iron would be fulfilled. "It seems probable" states Penrose[4] "that a large number, if not most of the workable deposits of manganese in America were laid down in local basins by the processes just described."

In India the manganese deposits of the Dhárwár Series are believed by L.L. Fermor[5] to have been formed in small basins: "The evidence of the manganese deposits shows that there must have been many basin shaped areas formed in various parts of the region of deposition. Some of these basins must have been of large size, of the nature of large lakes, or small seas, whilst others may have been quite small." Concerning the Gondite Series he states: "It seems as if we can say with some degree of certainty that these manganiferous sediments were deposited in circumscribed areas of the nature of lagoons or that they were partly deposited in areas of considerable extent such as a comparatively large lake"[6]. Bucher states that siderite

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1 "The Geology of the Dolgelley District (Merionethshire)". Proc. Geol. Assoc. Vol.38. pp.272. (1927).
2 "On the occurrence of spherulitic siderite and other carbonates in sediments". Q.J.G.S. Vol.lxxxi. pp.685. (1925).
3 Amer. Jour. Sci. 3rd Series. Vol.xiv. pp.139. 1877.
4 Penrose, R.A.F. op.cit. pp.559.
5 op. cit. pp.284.
6 op. cit. pp.318.

is deposited as a gel in stagnant seas.[1]

(vii) Finally the depsoition of the Harlech Grits marks the first transgression of the Palaeozoic seas on to the old Pre-Cambrian continent. When such a major transgression begins, it is usual to find that the waters first occupy localized areas of depression, forming small seas and lakes, before further subsidence and transgression gives use to a well formed geosyncline. After the formation of the Harlech Grits, the Menevian Beds and the LingulaFlays show a marked deepening of the waters with transgression and these beds can be more readily correlated in the various areas. By these times the localized basins of the earliest Cambrian had become joined into one layer sea.

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1 "On Colites and Spherulites". Journ. Geol. Vol.XXII. pp.593.

EXPLANATION OF PLATES.

Plate 1.

Fig.1. General view of the mudstone-grit succession immediately above the ore; St. John's Church, Barmouth. The ore band is situated at the base of the level entrance.

Fig.2. A level on slopes above Barmouth. The ore occurs a little distance below the hammer. Note the blocky weathering of the "bluestone" and the massive character of the "Bluestone Grit".

Fig.3. Collapsed workings on N.E. spur of Diphwys. In the picture are also seen the uppermost beds of the Rhinog Grits (on the extreme right) and the "Forty Feet Grit" above the ore. The intervening mudstones are well cleaved.

Fig.4. West side of Mynydd Cwm Mynach; showing the ore (immediately above bush on left), the "bluestone" and the "Bluestone Grit" (base marked by hammer).

Fig.5. East side of Cwm Mynach Valley. The hammer rests on the top of the manganese ore and the "Bluestone Grit" marks the sudden disappearance in the striped banding of the bluestone.

Plate 2.

Fig.1. View of working in the Moelfre Mines on the western slopes of Moelfre. The hammer marks the base of the "Bluestone Grit".

Fig.2. Close-up view of the ore and the "bluestone" Hendre Mines N.W. slopes of Moelfre.

Fig.3. Hammer rests of Bluestone Grit (cleaved), above a level on the N.W. slopes of Moelfre.

Fig.4. General view of the strata above the ore. Hafod-y-Llyn.

Fig.5. The ore is below the water and the hammer marks the base of the "Bluestone Grit", Hafod-y-Llyn.

Plate 3.

Fig.1. S.W. slopes of Moel Ysgyfarnogod. The map case shows position of the ore, and the hammer rests on the "Bluestone Grit".

Fig.2. More general view of same, showing the alternation of the mudstone succession between the ore and the "Forty Feet Grit."

Fig.3. General view of workings on the western slopes of Mynydd Cwm Mynach. Note the massive Rhinog Grits on left of picture and the massive "Forty Feet Grit" which caps the mountain.

Fig.4. General view of the workings on the N.W. slopes of Y Llethr.

Fig.5. General view of workings on Moel Ysgyfarnogod. The much thickened "Forty Feet Grit" is much in evidence.

Plate 4.

Fig.1. The contorted nature of the garnet-quartz rock, with the harder bands standing out well on weathering. Lower workings of Hendre Mines N.W. slopes of Moelfre.

Fig.2. Nearer view of same.

Fig.3. Specimen of Bluestone from the Egryn Mines N. of Barmouth about 3/4 natural size.

Fig.4. Pyritiferous band in the bluestone. Hendre Mines N.W. slopes of Moelfre (see p. 108). 2/3 natural size.

Fig.5. Pyritiferous layer below the manganese ore, showing very well developed pyrite crystals. Hendre Mines N.W. slopes of Moelfre. 3/4 natural size.

Plate 5.

Fig.1. Specimen of quartz-chlorite-biotite-spessartite rock from bluestone, with contorted carbonate layer. Hendre Mines, N.W. slopes of Moelfre. 2/3 natural size.

Fig.2. Garnet-quartz rock. Hendre Mines, N.W. slopes of Moelfre. 2/3 natural size.

Fig.3. Biotite-bearing bluestone with intercalated irregular layers of horny ore material. Hendre Mines. 3/4 natural size.

Fig.4. Specimen of the calcite-muscovite bearing bluestone. Hendre Mines; 1/2 natural size.

Fig.5. The folded sphaerodialogite band. St. John's Church, Barmouth. 1/2 natural size.

Plate 6.

Fig.1. Manganese ore. Normal chocolate-red-yellow development. Workings near Cell Fechan, 1/4 ml. N. of Barmouth. 2/3 natural size.

Fig.2. Manganese ore: with cream ore developed. W. side of Mynydd Cwm Mynach. 3/4 natural size.

Fig.3. Manganese ore, with well developed red and black banded ore. S. side of Moel Ysgyfarnogod. 2/3 natural size.

Photomicrographs.

Plate 7. The Manganese ore.

Fig.1. Normal ore, showing well developed contraction cracks in the yellow material with diminished development in the chocolate-red material. Magnification x 12 diams.

Fig.2. The laminated character of the normal chocolate-red material. Magnification x 25 diams.

Fig.3. Similar laminated character developed with bluish-black pyrolusite bearing band. Note also the regularly developed contraction cracks. Magnification x 12 diams.

Fig.4. Spheroidal bodies of yellow material set in normal chocolate-red material. Note how the lamination of the red band conforms smoothly to the irregularities caused by these spheroids. Magnification x 12 diams.

Fig.5. Spheroidal bodies within yellow material. Magnification x 12 diams.

Fig.6. To show the difference in character between the pyrolusite of the normal black bands (in south of field) and the pyrolusite formed by break down of carbonate on weathering. Magnification x 12 diams.

Plate 8.

Fig.1. Abnormally well developed garnets in yellow ore material. Magnification x 115 diams.

Fig.2. The same with nicols crossed.

Fig.3. The sharp junction between red and yellow bands. Magnification x 115 diams.

Fig.4. Showing sharp junction of ore band with mudstone material. The ore material shows well developed garnets and the mudstone good magnetite. Magnification x 115 diams.

Fig.5. Normal bluestone containing spheroidal body of "ore" material. Good authigenous magnetite is abundantly developed in the mudstone. Magnification x 35 diams.

Fig.6. The same, with nicols crossed.

Plate 9.

Fig.1. Mudstone matrix of the pyrite band below ore, E. side of Llyn Dywarchen, showing abundant authigenous magnetite. Magnification x 35 diams.

Fig.2. Mudstone matrix of pyrite band below the ore; E. slopes of Diphwys, showing abnormally abundant authigenous magnetite. Magnification X 35 diams.

Fig.3. Mudstone with layer of "concentrated" heavy minerals. (See p.). Magnification x 115 diams.

Fig.4. Sphaerodialogite band, St. John's Church, Barmouth, showing sharp junction of the band with the mudstone, a contraction crack, infilled with chalcedony and the black cross extinction phenomenon. Nicols crossed. Magnification x 35 diams.

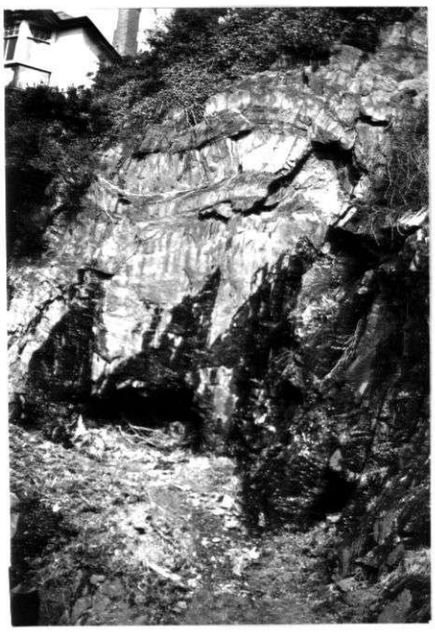
Fig.5. Well developed minute garnets in the quartz-garnet rock of the Hendre locality. Magnification x 125 diams.

Fig.6. The same with nicols crossed.

Plate 10.

Fig.1. "Heavy Mineral" separation from "Bluestone Grit", St. John's Church, Barmouth. Magnification x 35 diams.

Fig.2. Separated magnetite showing good octahedral crystals, from the bluestone. Magnification x 35 diams.



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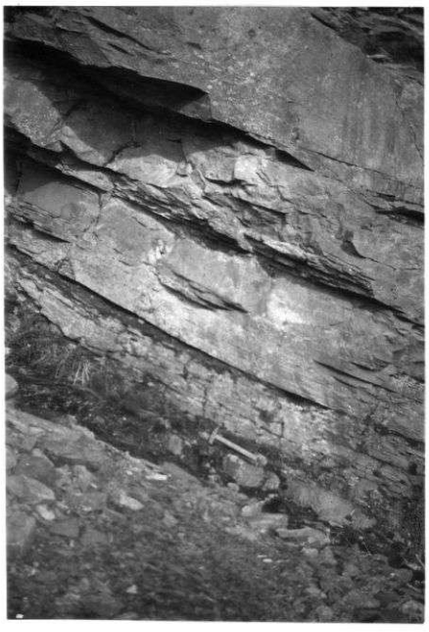

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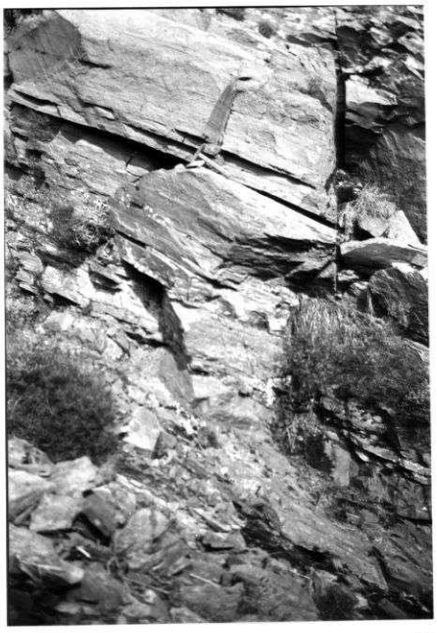

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Plate 2

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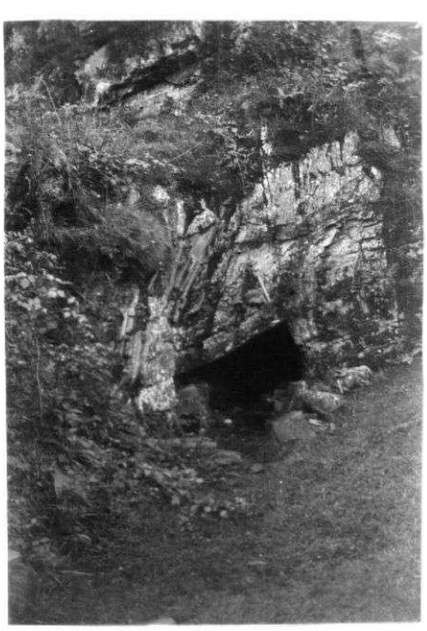

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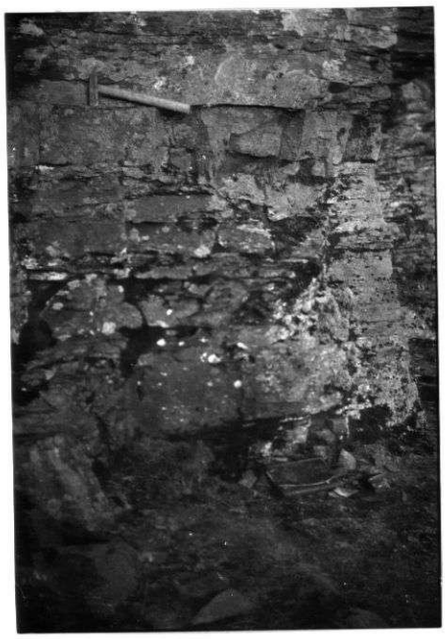
Plate 3



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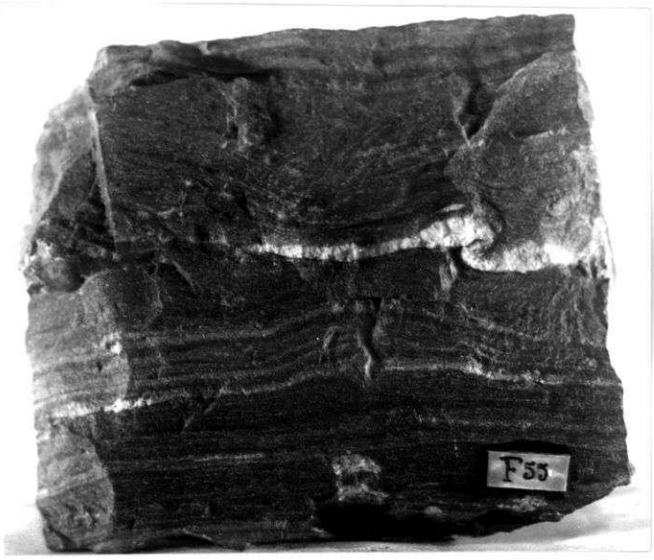

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Plate 6

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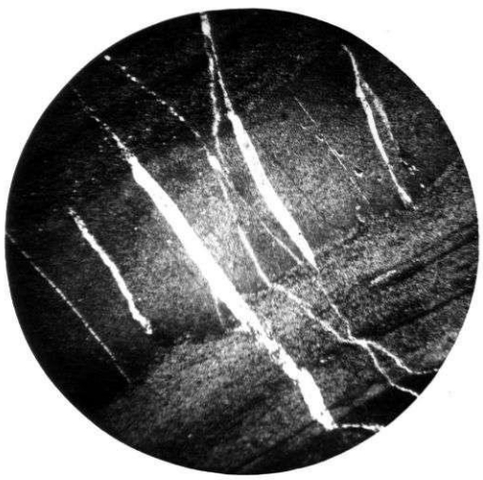
Plate 7



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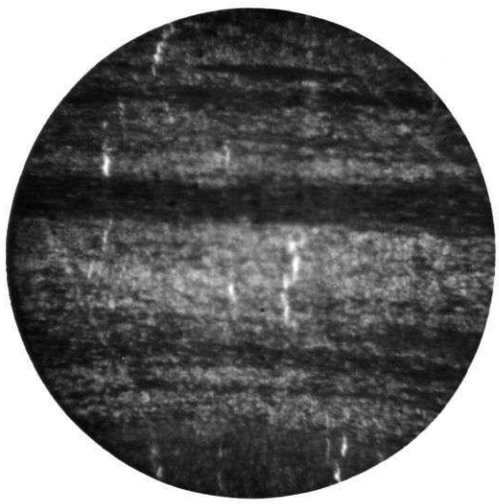

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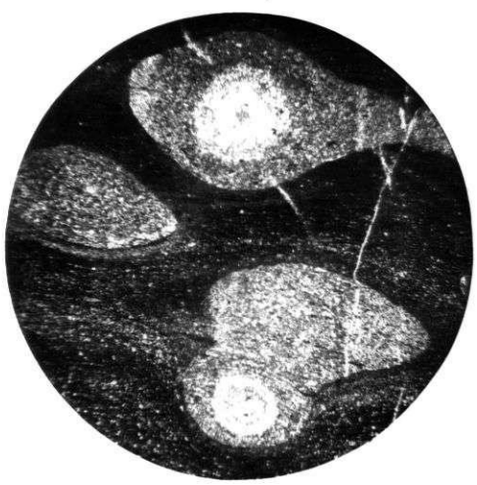

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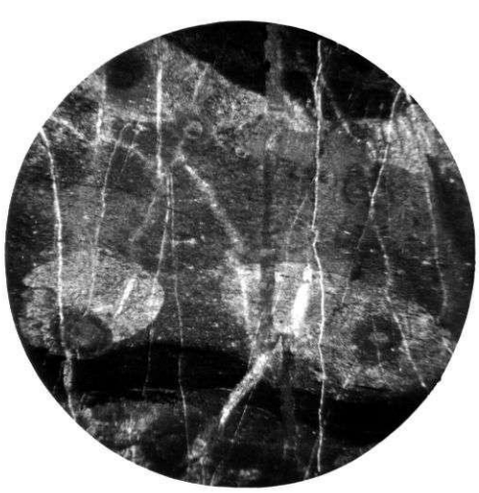

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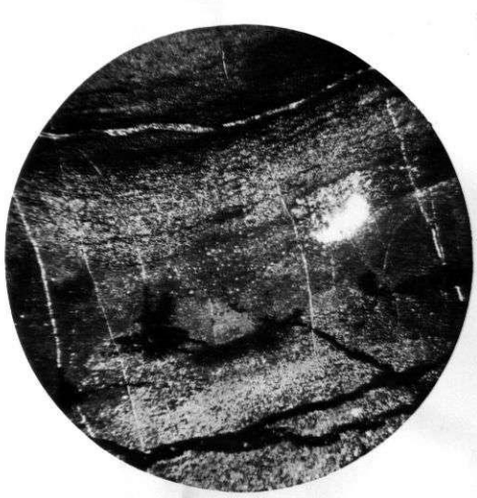

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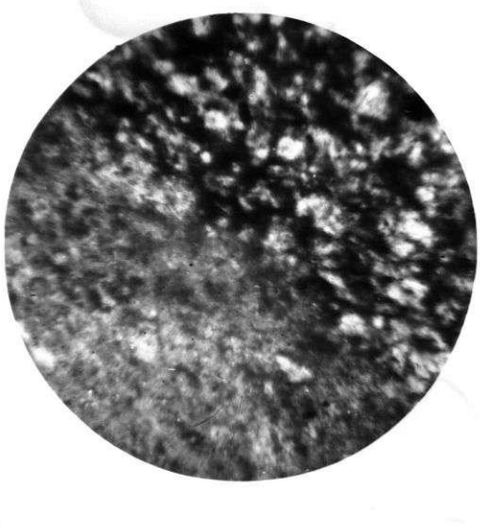

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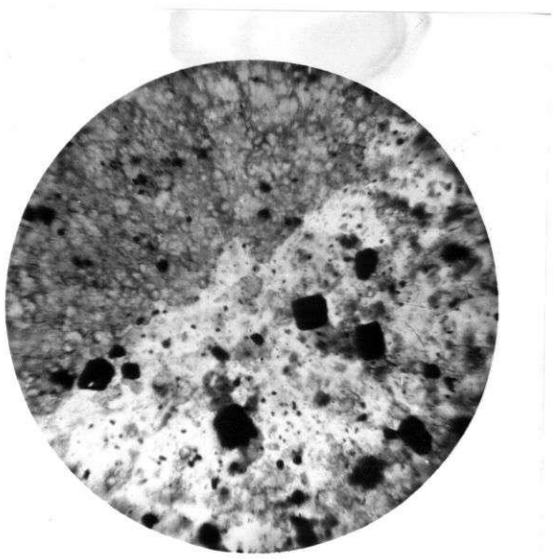

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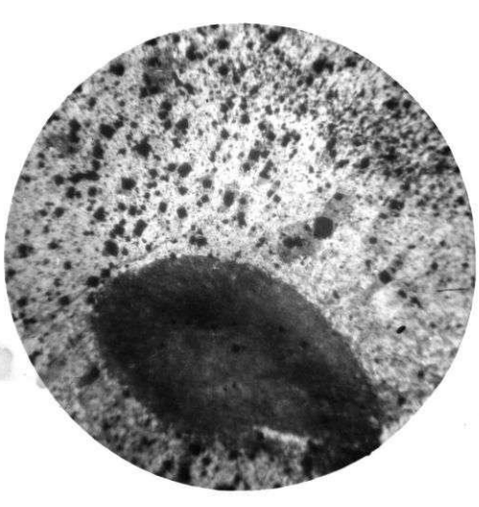

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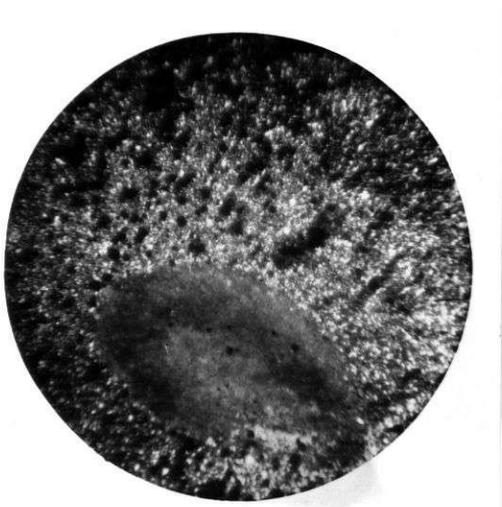

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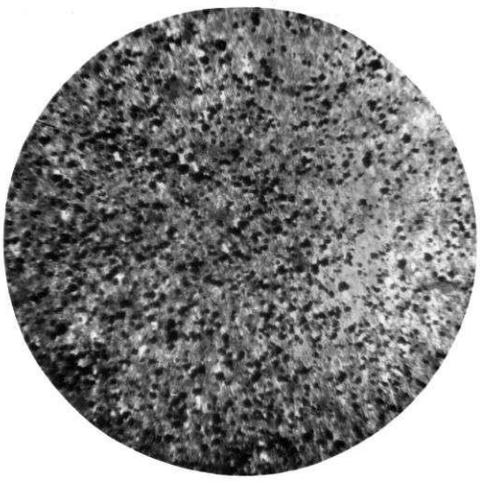

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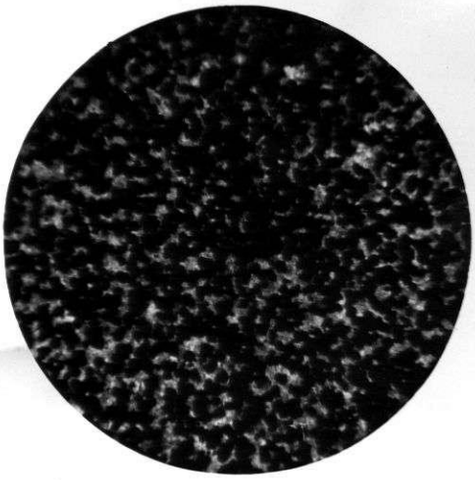

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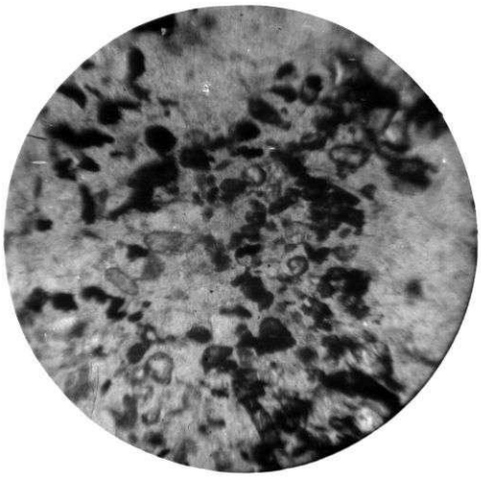

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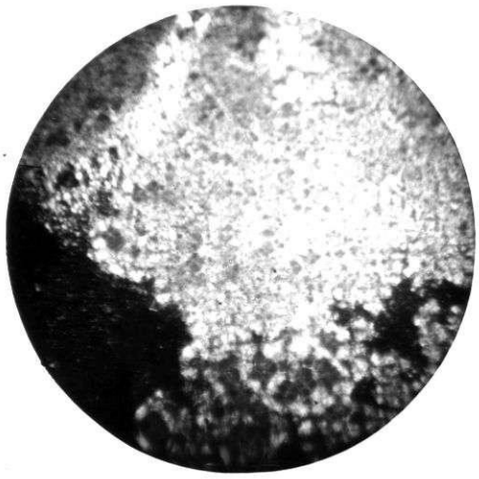

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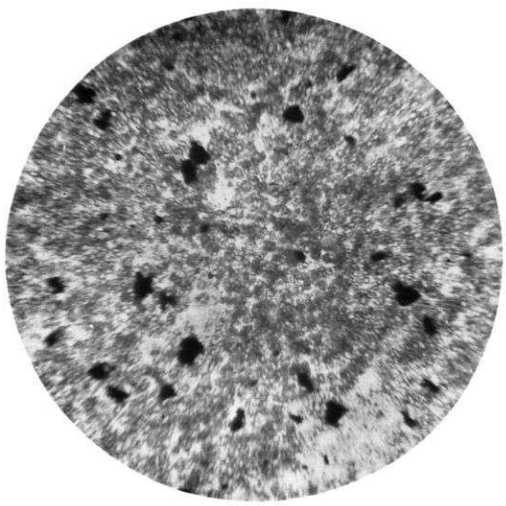

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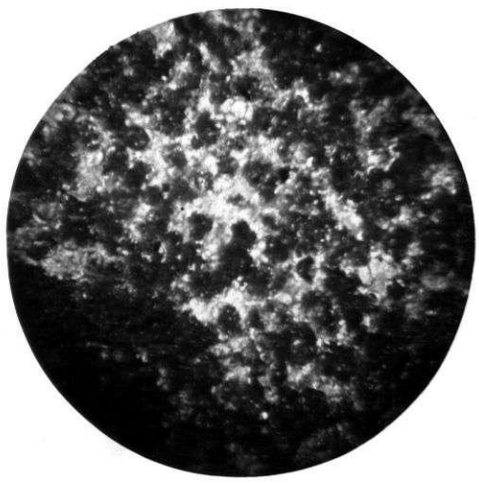

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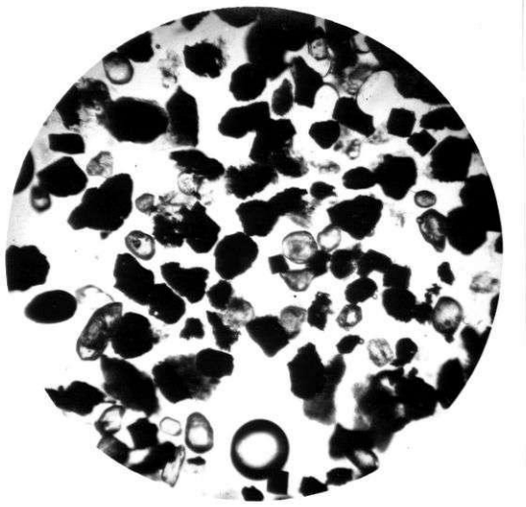
Plate 10



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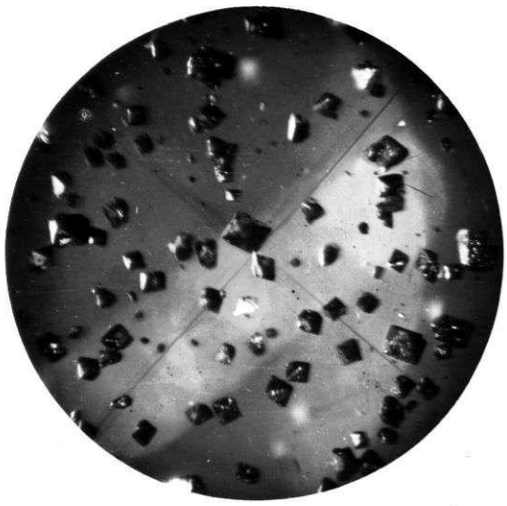

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